

Technology for Space Station Evolution Workshop
Dallas, Texas - January 16-19, 1990

Title:

TECHNOLOGIES FOR ECLSS EVOLUTION

Presenter:

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TECHNOLOGY FOR SPACE STATION EVOLUTION WORKSHOP
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Presentation Title

TECHNOLOGIES FOR ECLSS EVOLUTION

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Introduction

In this presentation characteristics of existing and advanced physio-chemical technologies are discussed for the Atmosphere Revitalization (AR), Water Recovery and Management (WRM), and Waste Management (WM) subsystems of the Space Station Freedom Environmental Control and Life Support System (ECLSS). All technologies discussed have undergone some degree of experimental testing, and many competed for the space station ECLSS baseline. The primary qualitative advantages and disadvantages of each technology are summarized. Technologies are discussed for the following systems: CO₂ removal, CO₂ reduction, O₂ generation, trace contaminant control, urine processing, hygiene water processing, potable water processing, and waste processing.

OVERVIEW

Introduction:

Existing and advanced physio-chemical technologies are discussed for the Atmosphere Revitalization (AR), Water Recovery and Management (WRM), and Waste Management (WM) subsystems of the space station ECLSS.

Main Body:

Discuss operation, advantages, disadvantages of following:

I. Atmosphere Revitalization (AR)

CO₂ Removal
CO₂ Reduction
O₂ Generation
Trace Contaminant Control

II. Water Recovery and Management (WRM)

Urine Processing
Hygiene Water Processing
Potable Water Processing

III. Waste Management (WM)

Summary:

List of technologies.

CO₂ Removal

Baseline Technology

Four-Bed Molecular Sieve (4BMS)

The 4BMS is composed of two adsorbing sorbent beds, one a desiccant bed for water vapor removal, the other a Zeolite 5A molecular sieve for trapping CO₂. This bed pair operates in parallel with an identical pair of beds in the desorbing mode. Adsorption of CO₂ from the process air is accomplished at low temperature. The adsorbing bed is then heated to desorb the CO₂ to a reduction device. The 4BMS is a mature, flight-proven technology. A similar system was flown on Skylab, where CO₂ was desorbed to space. The 4BMS has no significant impacts on other space station systems, although its power requirement and volume are higher than other available technologies.

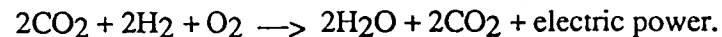
Candidate Substitute Technologies

Solid Amine Water Desorbed (SAWD)

The SAWD operates similarly to the 4BMS, although no desiccant beds are required. The SAWD uses steam-heated solid amine (WA-21) beds to adsorb CO₂. Desorption is accomplished by steam-heating the CO₂-laden beds. Solid amines degrade more rapidly than Zeolites, decreasing bed efficiency and increasing bed changeout frequency and resupply. SAWD also penalizes the ECLSS by requiring hygiene water, which is eventually vented in vapor form to the Temperature and Humidity Control System (THC), increasing the load on the cabin condensing heat exchanger. Since condensate is used for potable water, the loss of hygiene water due to the SAWD appears as a gain in the potable supply. SAWD has the advantage that desorption takes place at cabin pressure rather than at the near vacuum conditions required by the 4BMS.

Electrochemical Depolarized CO₂ Concentrator (EDC w/H₂)

The EDC reacts H₂ and O₂ inside an electrochemical cell with cabin air containing CO₂, producing two output streams. The reaction is :



The output from the anode-side cavity of the cell has a high concentration of CO₂ and some H₂, while the cathode-side cavity output contains air with a low CO₂ concentration that is returned to the cabin. The EDC eliminates inefficient cycling required by technologies that must repeatedly heat and cool adsorbing/desorbing beds. EDC has the disadvantages of consuming oxygen and producing water vapor, increasing the respective loads on the oxygen generation and humidity control systems. EDC is also a safety hazard due to the potential for hydrogen leakage into the cabin atmosphere, which could lead to a fire or explosion. No other CO₂ removal technology employs H₂ in the removal process.

AR - CO₂ REMOVAL

Baseline Technology

Four-Bed Molecular Sieve (4BMS)

- + Mature flight-proven technology.
- + Low system impacts.
- High power and volume.

Candidate Substitute Technologies

Solid Amine Water Desorbed (SAWD)

- + Only two sorbent beds required, reducing complexity relative to the 4BMS.
- + Ambient pressure desorption. Vacuum pressures not required.
- Impacts to Temperature and Humidity Control system and hygiene water supply.
- Degradation of solid amine beds reduces efficiency and increases resupply.

Electrochemical Depolarized Concentrator (EDC w/H₂)

- + Eliminates inefficient cycling.
- Potential for hydrogen leakage is safety concern.
- System impacts on O₂ Generation and Temperature and Humidity Control systems.

CO₂ Removal

Air Polarized CO₂ Concentrator (APC or EDC w,wo/H₂)

This technology is simply an EDC not requiring H₂ for the CO₂ removal process. The capability to operate without hydrogen reduces the safety concern, although the APC will likely alternate between operating with and without hydrogen to minimize system power requirements. However, switching between operating with and without H₂ accelerates degradation of the cell electrode catalyst. The APC requires an O₂/CO₂ separator, slightly increasing its weight, power, volume, and complexity relative the EDC.

Two-Bed Molecular Sieve (2BMS)

The 2BMS is similar to the 4BMS, although the 2BMS utilizes a carbon molecular sieve (CMS) instead of Zeolite to adsorb CO₂. CMS material preferentially adsorbs CO₂ over water vapor, eliminating the need for the two desiccant beds found in the 4BMS. This reduces system power, weight, volume, and complexity relative to the 4BMS without any additional system impacts. CMS material also desorbs at a lower temperature than Zeolite, further decreasing power requirements. The 2BMS is still under development.

Membranes

The use of membrane technology to effectively concentrate CO₂ would likely result in a simple, light, small, low power CO₂ removal system. However, the gas selectivity of current membrane technology is inadequate. Instead of filtering all other gases besides CO₂ from the process air to produce a stream of high CO₂ concentration, the membranes also filter out some CO₂ and return it to the cabin. This inefficient process requires large membranes to remove relatively small quantities of CO₂.

AR - CO₂ REMOVAL

Air Polarized CO₂ Concentrator (APC or EDC w,wo/H₂)

- + Safety concern reduced.
- W/Wo H₂ operation reduces power consumption, but accelerates electrode catalyst degradation.
- O₂/CO₂ separator decreases power, weight, volume relative to EDC w/H₂.
- Advanced version of EDC still under development.

Two-Bed Molecular Sieve (2BMS)

- + Elimination of desiccant beds reduces system power, weight, volume, complexity.
- + Carbon molecular sieve desorbs at lower temperature than Zeolite, reducing power usage.
- System still under development.

Membranes

- + Potential for low weight, power, volume, complexity.
- Highly inefficient due to poor gas selectivity.

CO₂ Removal

Fluid Interfaces

The space station must be designed to easily incorporate advanced technologies that could foreseeably replace the baseline technologies in the future. Designing the station for easy on-orbit technology replacement is referred to as scarring the station. Scarring ensures that all interfaces required by an advanced technology will be available when it comes time to replace the old technology. These interfaces include any fluid interfaces, such as a line to the liquid coolant loop, a gas vent line to trace contaminant control, or a CO₂ output line to the Bosch. Fluid interfaces for advanced technologies not required by the baseline technology are plumbed from the module standoffs to the rack(s) expected to house the future technologies and capped off. These temporarily unused fluid lines are station scars. The included table is a list of the fluids input to and output from CO₂ technologies. These fluid interfaces were obtained by studying available schematics for each technology. Similar tables for the other subsystems (urine processing, trace contaminant control, etc.) are included in this packet, but are not presented.

CO₂ REMOVAL

FLUID INTERFACES

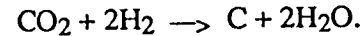
TECHNOLOGY	FLUID INTERFACES	
	LINE IN	LINE OUT
Four-Bed Molecular Sieve	Cabin Air Liquid Coolant	Return Air CO ₂ , Liquid Coolant
Two-Bed Molecular Sieve	Cabin Air Liquid Coolant	Return Air CO ₂ , Liquid Coolant
EDC	Cabin Air, N ₂ Purge Liquid Coolant, H ₂	Return Air, H ₂ /CO ₂ , Liquid Coolant
SAWD	Cabin Air Hygiene Water	Return Air Steam Pressure Vent, CO ₂
APC	Cabin Air Liquid Coolant H ₂ , N ₂ Purge	Return Air, H ₂ /CO ₂ Liquid Coolant
Membranes	Cabin Air	Return Air CO ₂

CO₂ Reduction

Baseline Technology

Bosch Reactor

Carbon dioxide is reacted with hydrogen at high temperature (1050°F) in the presence of a nickel catalyst, producing solid waste carbon and water for the potable supply. The reaction is:

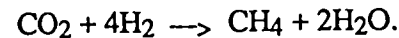


A single pass through the Bosch reactor reduces only about 11% of the input CO₂, with efficiency decreasing as carbon builds up in the collection cartridges. Complete, 100% conversion is achieved by continuously recirculating the process gases. Bosch carbon cartridges must be resupplied; however, the issue of carbon cartridge replacement vs. replacement of the entire core reactor is still undecided.

Candidate Substitute Technologies

Sabatier Reactor

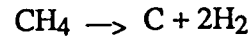
Carbon dioxide is reacted with hydrogen at high temperature in the presence of a ruthenium catalyst on a granular substrate, producing methane and water. The reaction is:



Sabatier has the advantage of being smaller and requiring much less power than Bosch; however, the toxic methane it produces must be vented to space or stored at a high weight and volume penalty. Both of these methods are currently impractical. Sabatier would be a very attractive technology if its product methane could be used as a propellant for space station attitude control resistojets. The Sabatier reactor has a conversion efficiency greater than 98%; however, anything less than 100% results in the loss of oxygen molecules in the form of unreacted CO₂. Loss of O₂ combined with loss of H₂ in the product CH₄ is a costly disadvantage of Sabatier. The water and oxygen supplies will be slowly depleted, ultimately necessitating increased resupply.

Advanced Carbon Reactor (ACR)

The ACR consists of a Sabatier reactor, a gas/liquid separator to remove product water from methane, and a carbon formation reactor (CFR) to reduce methane to carbon and hydrogen. The reaction inside the carbon formation reactor is:



The ACR carbon collection cartridges pack carbon more neatly than the Bosch, reducing resupply. A disadvantage of the ACR is that both the catalytic and pyrolytic versions of the CFR operate above 1600°F, which may present materials problems. The ACR is still under development.

CO₂ Electrolysis

See the section on O₂ Generation. CO₂ electrolysis is a dual-function technology, where CO₂ is reduced to produce oxygen. CO₂ electrolysis does not require hydrogen as a reactant for the reduction process, although it therefore produces no water for the potable supply. Some hydrogen will appear in the output stream due to electrolysis of water vapor.

AR - CO₂ REDUCTION

Baseline Technology

Bosch Reactor

- + 100% CO₂ conversion.
- Single pass CO₂ conversion efficiency only 11%.
- Carbon collection device must be resupplied.

Candidate Substitute Technologies

Sabatier Reactor

- + Potential for lowest weight, power, volume.
- Incomplete CO₂ conversion necessitates water resupply.
- High weight and volume penalty for waste gas storage.

Advanced Carbon Reactor (ACR)

- + High density carbon packing reduces resupply.
- High temperature operation may present materials problems.
- Technology still under development.

CO₂ Electrolysis

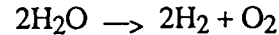
- + Dual function technology.
- + Electrolysis of water vapor reduces humidity.
- + H₂ not required as a reactant.
- Water not produced for the potable supply.
- Potential for carbon monoxide leakage.
- High operating temperatures present materials problems.
- Requires Boudouard reactor.
- New technology still under development.

O₂ Generation

Baseline Technology

Static Feed Water Electrolysis (SFWE)

The SFWE electrolyzes hygiene water to produce oxygen. The reaction is:



Water resting statically in a feed compartment diffuses as a vapor through the water feed membrane and into an aqueous KOH electrolyte. This passive water feed mechanism has the advantage of no moving parts. Oxygen gas is produced at the anode of the electrolysis cell, while hydrogen is produced at the cathode. Product hydrogen is sent to the CO₂ reduction system. The SFWE is a mature technology that has been tested extensively.

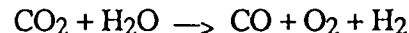
Candidate Substitute Technologies

Liquid Anode Feed Solid Polymer Electrolysis (SPE)

Similar in concept to the SFWE, the SPE electrolyzes water using a solid polymer electrolyte (sulfonated perfluoro-linear polymer). SPE requires that feed water be in direct contact with the cell anode to provide cooling during the electrolysis process. The need for two liquid/gas separators and a deionizer bed increases SPE system complexity relative to the SFWE. The deionizer is needed to remove contaminants from the hygiene feed water that could otherwise corrode the anode. SPE cell stack technology has been tested extensively, and has been used successfully in submarines.

CO₂ Electrolysis

CO₂ electrolysis is a dual-function technology, simultaneously performing carbon dioxide reduction and oxygen generation. By combining two functions into one technology, total AR system weight, power, volume, and complexity may be reduced. CO₂ is electrolyzed using a solid oxide electrolyzer, producing O₂ and CO. The electrolysis cell reaction is:



CO is then catalytically decomposed in a Boudouard reactor into solid carbon and CO₂, and this CO₂ is recycled to the electrolysis unit. Water vapor in the process stream is also electrolyzed, which helps control cabin humidity. CO₂ electrolysis places no burden on the hygiene water supply, virtually eliminating two-phase (liquid/gas) processing, although it penalizes the potable water supply by being the only technology performing CO₂ reduction that does not produce potable water. CO₂ electrolysis operates at very high temperatures (above 1600°F), presenting materials problems, and may have the potential for dangerous carbon monoxide leakage. The CO₂ electrolyzer and particularly its associated Boudouard reactor are new technologies requiring further development.

Water Vapor Electrolysis (WVE)

WVE electrolyzes water vapor directly from cabin air, producing oxygen and hydrogen. Cabin air containing moisture is fed to the anode-side compartment of the SFWE-style electrolysis cell, producing an O₂-enriched stream at the anode and hydrogen at the cathode. WVE helps control cabin humidity and, having few interfaces, lends itself as a portable technology to augment the central O₂ generation system for situations when additional oxygen is needed, such as when the crew gathers for a significant period of time.

AR - O₂ GENERATION

Baseline Technology

Static Feed Water Electrolysis (SFWE)

- + Extensively tested, mature technology.
- + Passive water feed mechanism has no moving parts.

Candidate Substitute Technologies

Liquid Anode Feed Solid Polymer Electrolysis (SPE)

- + Extensively tested, mature cell stack technology.
- Two liquid/gas separators and a deionizer increase system complexity.

CO₂ Electrolysis

- + Dual function technology.
- + No penalty to the hygiene water supply.
- + Eliminates two-phase (liquid/gas) processing.
- + Electrolysis of water vapor reduces cabin humidity.
- Potential for carbon monoxide leakage.
- High operating temperatures present materials problems.
- Requires Boudouard reactor.
- New technology requiring further development.

Water Vapor Electrolysis (WVE)

- + Helps control cabin humidity.
- Potential as a portable technology to augment centralized system.

Trace Contaminant Control

Baseline Technology

Carbon Adsorption Beds with Catalytic Oxidizer

Charcoal (carbon) adsorption beds coupled with platinum catalytic oxidizers remove trace contaminants, such as freons and aromatics, from cabin air. The charcoal beds, similar to those found on previous manned space flight missions, are expendable, incurring a large resupply penalty. This costly disadvantage may eventually be eliminated by developing a safe regenerable system. Pre and post sorbents are required for the oxidizer to prevent catalyst poisoning by halogenated hydrocarbons and acidic gases, such as sulfur oxides. These additional sorbents increase system complexity.

Candidate Substitute Technologies

Reactive Bed Plasma (RBP)

RBP decomposes contaminants at low temperature (250°F) using a synergistic combination of plasma and catalyst. Process air passes through an annular reactor filled with alumina catalyst, where it is electrically ionized into plasma. The main function of the catalyst is to increase the time contaminant molecules spend in the active plasma region, where plasma-generated high energy electrons and subsequently produced species (mainly active oxygen) oxidize toxic materials. In addition, RBP can perform as a highly efficient electrostatic precipitator to collect and deactivate hazardous particulate material. The RBP system includes low temperature (150°F) regenerable post-treatment of toxic reaction products, particularly nitrous oxides. RBP completely reduces methane, and the system is very difficult to poison. The RBP system currently has a high power requirement of about 1000 W. Another disadvantage is that RBP performance may be degraded by electromagnetic interference, although the magnitude of this problem is presently unclear. RBP is currently under development.

AR - TRACE CONTAMINANT CONTROL

Baseline Technology

Carbon Adsorption Beds with Catalytic Oxidizer

- + Highly mature technology.
- Expendable charcoal beds incur a large resupply penalty.
- Pre/post sorbents for oxidizer are required to avoid catalyst poisoning.

Candidate Substitute Technologies

Reactive Bed Plasma (RBP)

- + Acts as a highly efficient electrostatic precipitator.
- + Low temperature (250°F) operation.
- + Complete methane reduction.
- + Extremely difficult to poison.
- High power requirement.
- Conversion of CO to CO₂ burdens the CO₂ reduction system.
- Performance may be degraded by electromagnetic interference.
- New system currently under development.

Urine Processing

Baseline Technology

Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES)

Before entering the TIMES unit, process urine/flush water is pretreated with oxone and sulfuric acid to fix free ammonia, inhibit microbial growth, control odor, and reduce foaming. The pretreated urine/flush water enters the TIMES through two parallel heat exchangers in contact with the hot side of a thermoelectric heat pump. The heated waste water then flows through hollow fiber membranes that make up the evaporator section of the subsystem, consisting of 600 Nafion tubes assembled into six bundles of 100 tubes each. Long term reliability of the joints connecting the Nafion tubes to the bundle headers is currently a TIMES concern. Water diffuses through the membranes and evaporates from their outer surfaces, which are maintained at low pressure. This steam flows to the main condenser, which is in contact with the cold side of the thermoelectric heat pump. Partially condensed, the steam then flows to an air-cooled heat exchanger, where the condensation process is completed. Latent heat is recovered and reused in the evaporative process. The condensate is tested for water quality and, if acceptable, is delivered as product water to the hygiene processor by a centrifuge-type pump. The pump acts as a gas/liquid separator since it removes non-condensable gases entrained in the condensate stream. Unacceptable condensate is reprocessed. With water recovery efficiency less than 100% (90-95%), the TIMES process involves brine storage, which is a weight, volume, and resupply penalty.

Candidate Substitute Technologies

Vapor Compression Distillation (VCD)

VCD maintains a vapor/liquid interface using centrifugal force created by a rotating drum. This is more complicated than the static phase separation process employed by the TIMES. Water is evaporated from a thin film of process waste water flowing over the inner surface of a rotating evaporator/condenser drum. The water vapor is compressed, raising its saturation temperature, then directed out of the drum and against its outside surface, where it condenses. The latent heat of condensation is transferred passively from the outside to the inside of the drum through its thin metallic wall, providing the latent heat required to evaporate the next batch of incoming waste water. This passive latent heat transfer makes VCD an energy efficient process. After startup, the only energy used by the process is for water vapor compression and for overcoming mechanical and thermal inefficiencies. Unevaporated waste water is recirculated until the solids concentration builds up to a predetermined level, at which time the concentrated brine is removed for storage. The VCD brine storage penalty is nearly identical to that of the TIMES. A disadvantage of VCD is that its rotating/vibrating parts may create forces that could disrupt the space station microgravity environment. Additionally, mechanical reliability of the peristaltic feed pump is still in question.

WRM - URINE PROCESSING

Baseline Technology

Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES)

- + Waste water phase separation is a static process.
- Membrane mechanical reliability questionable over long term.
- Less than 100% water recovery necessitates brine storage.

Candidate Substitute Technologies

Vapor Compression Distillation (VCD)

- + Produces slightly higher water quality and processes higher flow rates than TIMES.
- + Lowest power consumption due in part to passive latent heat recovery.
- Dynamic waste water phase separation more complex than TIMES static separation.
- Less than 100% water recovery necessitates brine storage.
- Mechanical reliability of peristaltic feed pump questionable.

Urine Processing

Air Evaporation System (AES)

In the AES, pretreated urine is pumped through a particulate filter to a wick package using a pulse feed technique. The pulse and urine flow rate are controlled by a feed pump that responds to the relative humidity of air leaving the wick package and the amount of liquid processed. Sufficient time is provided between pulses to allow the volume of urine to be distributed before the next pulse. A circulating heated air stream evaporates water from the urine, leaving urine solids in the wicks. When sufficient urine solids accumulate in the wicks, the feed pump is shut off and the loaded wicks are dried down and replaced with a new wick package. Storage of spent wick packages is likely to require less volume than brine storage. During dry-down, humid air leaving the wick package passes through a condensing heat exchanger. A water separator downstream of the condenser removes water from the air stream and pumps it to the product water loop. The complete dry-down procedure results in nearly 100% water recovery. Precise waste water feed control is critical to water recovery efficiency. Feeding too much waste water will saturate the sponge-like wicks, causing waste water to drip off the wicks and continue downstream before entrained contaminants can be absorbed. The complex feed control still requires further development. The AES was tested successfully in manned chamber tests by McDonnell Douglas in the late 1960's, and involves a relatively simple, reliable process. The AES operates at ambient pressure, eliminating potential leakage problems and system impacts associated with vacuum pressures. AES is tolerant of solid precipitates, eliminating the need for an oxidizing pretreatment. Oxone urine pretreatment is required by the TIMES to keep solid precipitates in solution during processing, but oxone is a corrosive, reactive chemical. Nonoxidizing pretreatments, which are safer and easier to handle than oxone, do not hold solid precipitates in solution. This is ideal for the AES, where solids must precipitate out into the wicks. The main disadvantage of AES is that it is an energy-intensive process, requiring much more power than its competitors. Methods for reducing energy consumption are being studied, all of which will likely increase system complexity.

Vapor Phase Catalytic Ammonia Removal (VPCAR)

VPCAR is based on a catalytic chemical process where impurities that vaporize with the process water are oxidized to innocuous gaseous products. The process employs two catalyst beds. In the first bed ammonia is oxidized to a mixture of nitrogen and nitrous oxide, and volatile hydrocarbons are oxidized to carbon dioxide and water vapor. In the second bed nitrous oxide formed in the first bed is catalytically decomposed into oxygen and nitrogen. VPCAR requires neither pretreatment nor posttreatment. As a first-generation system VPCAR produces higher quality water than its more mature competitors. Recovered water has little ammonia, few hydrocarbons, and low conductivity, requiring only adjustment of its pH to meet potable water standards. VPCAR employs the same potentially unreliable hollow fiber evaporator found in the TIMES, and has the additional disadvantage of operating at high temperatures of up to 850°F. VPCAR also requires brine storage, and the process impacts SFWE operation by consuming oxygen.

WRM - URINE PROCESSING

Air Evaporation System (AES)

- + Nearly 100% water recovery
- + Reliable, simple process.
- + Tolerant of solid precipitates. A nonoxidizing pretreatment becomes feasible.
- + Air evaporation loop operates at ambient pressure.
- + Storage of spent wick packages may require less volume than brine storage.
- Energy-intensive process.
- Complex control of wastewater feed to wicks requires further development.

Vapor Phase Catalytic Ammonia Removal (VPCAR)

- + First-generation system produces higher quality water than more mature competitors.
- + Pre/posttreatment not required.
- Consumes oxygen.
- Less than 100% water recovery necessitates brine storage.
- Operation at high temperature and pressure.
- More complex than other urine processors.
- New technology requiring further development.

Hygiene Water Processing

Baseline Technology

Reverse Osmosis (RO)

Non-phase change technologies, such as RO and MF, are chosen for hygiene water processing based on their low specific energy relative to phase change technologies and their ability to more readily process the high flow rates associated with hygiene water use. The RO system consists of an ultrafiltration (UF) unit and RO unit in series, each employing membranes for removing contaminants from waste water. Ultrafiltration is a process that filters most suspended solids and macromolecules, while allowing low molecular weight salts and water to permeate the membrane. As the first stage of the RO system, the primary function of UF is to remove large contaminants that would otherwise foul the RO membranes. In the RO unit a semipermeable membrane separates purified product water from input waste water. A pressure is applied to the waste water in excess of its osmotic pressure, reversing the normal osmosis process. Water spontaneously flows across the semipermeable membrane from the concentrated waste water solution to a less concentrated solution, resulting in product water with a reduced impurity concentration. The RO unit rejects all suspended solids, all macromolecules, and most low molecular weight salts, although current membranes are incapable of removing almost all groups of low molecular weight organics. Contaminant removal by membrane filtration is a more flexible method than removal by sorbent beds. Sorbent beds (employed by multifiltration) are designed to remove specific contaminants. An unexpected contaminant introduced into the hygiene water loop is more likely to be removed by the RO membranes than by the multifiltration sorbent beds. In addition, the unexpected contaminant may rapidly foul the sorbent beds. RO has the disadvantage of producing brine that must be processed by the urine processor. RO also requires posttreatment by multifiltration sorbent beds, which must be periodically changed out and resupplied.

Candidate Substitute Technologies

Multifiltration (MF)

See the section on potable water processing. MF system complexity is lower than RO, and it does not have the system impacts associated with brine handling (demand on urine processor and cycling of RO unit to allow for brine removal). MF has the disadvantage of being more sensitive to waste water characteristics than RO since its unibeds are designed to remove specific contaminants. MF is incapable of removing low molecular weight nonionic organics, particularly alcohols, ketones, and amides.

WRM - HYGIENE WATER PROCESSING

Baseline Technology

Reverse Osmosis (RO)

- + Filtration more flexible than contaminant removal by sorbents.
- + Low specific energy relative to phase change technologies.
- + Rejects all suspended solids, all macromolecules, and most low molecular weight salts.
- Incapable of removing almost all groups of low molecular weight organics.
- Requires brine processing by urine processor.
- Requires multifiltration posttreatment. Bed changeout is resupply, crew time penalty.

Candidate Substitute Technologies

Multifiltration (MF)

- + Low system complexity.
- + Low specific energy relative to phase change technologies.
- + Highest water recovery percentage.
- + Minimal system impacts.
- Incapable of removing low molecular weight, nonionic organics.
- Performance is sensitive to waste water characteristics.
- Bed changeout is high resupply, crew time penalty.

Potable Water Processing

Baseline Technology

Multifiltration (MF)

Potable water is obtained through multifiltration of condensate from the Temperature and Humidity Control (THC) subsystem and from water formed during the CO₂ reduction process. MF consists of a particulate filter upstream of six unibeds in series. Each unibed is composed of sorbent beds and ion exchange resin beds. After about 10-30 days the first unibed in the series will become contaminated. As the first bed to be exposed to input waste water, it becomes contaminated before the remaining unibeds downstream. Once its storage capacity is reached, this unibed is removed and the other five unibeds are moved up to fill the gap. A fresh unibed is placed at the end of the series. Unibed changeout is a resupply and crew time penalty, although the beds do not foul as quickly as the MF hygiene processor unibeds, which handle much dirtier waste water. Microbial growth is impeded by heating and chemically treating (iodine injected by a microbial check valve) the process water. MF has a higher water recovery percentage than RO.

Reverse Osmosis (RO)

See the section on hygiene water processing. RO/UF modules appear unnecessary for potable processing. Water quality entering the potable processor is relatively high. This water tends to pass through the RO/UF modules relatively unaffected, and the MF posttreatment unit winds up removing the majority of the entrained contaminants.

Electrodeionization

The electrodeionization process utilizes ion exchange resins and membranes to deionize contaminated feed water. Ion exchange membranes, used as barriers to bulk water flow, divide the system into three adjacent compartments - a diluting compartment bordered on either side by a concentrating compartment. Feed water enters the diluting compartment, which is filled with mixed-bed ion exchange resin. Ions in the feed solution react with the ion exchange resins, transferring through these resins in the direction of an electrical potential gradient applied across the compartments. Due to the semipermeability properties of the ion exchange membranes and the directionality of the potential gradient, ion concentration will decrease in the diluting compartment and increase in the concentrating compartments. The system outputs brine from the concentrating compartments and purified deionized water from the diluting compartment (conductivity as low as 0.1 microsiemen/cm). Pre- and posttreatment of the feed water is required to extract contaminants not removed by the electrodeionization process, including nonionic species, chlorine, and silica. Electrodeionization is capable of deionizing a wide range of feeds, from bulk salt removal to polishing of RO product water. In the electrodeionization system the ion exchange resin is continually electrically regenerated. Regeneration chemicals are not required, eliminating chemical handling, waste neutralization, and corrosion problems. Electrodeionization does not involve sorbent bed changeout required by MF and RO, although its pre/posttreatments will likely entail resupply and regular replacement of expendables by the crew. System disadvantages include high complexity relative to MF, and the production of brine that must be processed by the urine processor.

WRM - POTABLE WATER PROCESSING

Baseline Technology

Multifiltration (MF)

- + Low system complexity.
- + Minimal system impacts.
- + Highest water recovery percentage.
- Bed changeout is resupply, crew time penalty (not as high as MF hygiene processor).
- Incapable of removing low molecular weight nonionic organics.

Candidate Substitute Technologies

Reverse Osmosis (RO)

- + Filtration more flexible than contaminant removal using sorbents.
- Requires brine processing by urine processor.
- Incapable of removing almost all groups of low molecular weight organics.
- RO/UF modules appear unnecessary for potable processing. MF posttreatment removes majority of contaminants.

Electrodeionization

- High system complexity relative to RO and MF.
- Requires brine processing by urine processor.
- Pre/posttreatment required.

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D-9

Waste Management

Baseline Technology

Storage and Biodegradation

All solid waste is stored and returned to earth. Human solid waste is compacted and stored in canisters for biodegradation. When full these canisters are returned to earth and resupplied. This is a very simple, safe, low power method for handling waste, but large logistics penalties are involved. The logical improvement to storage is a waste management system capable of processing waste and recovering its useful constituents, an important step in developing a closed ECLSS. Storage and/or venting has been the method for waste management on all past manned space missions.

Candidate Substitute Technologies

Supercritical Water Oxidation (SCWO)

SCWO is a process in which oxygen and water above its supercritical temperature and pressure (705°F and 3190 psi) are used to oxidize organic waste materials without the presence of a catalyst. When water becomes supercritical its properties as a solvent change. Organic compounds, normally insoluble in water at standard temperature and pressure, become soluble in supercritical water. If sufficient oxygen is available and the reactor temperature and pressure are sufficiently high (750-1200°F and 3675 psi), these organic compounds, along with process atmospheric and trace contaminant gases, are completely oxidized to CO₂, H₂, and N₂. Additionally, inorganic salts become insoluble in supercritical water and precipitate from solution. Efficient processing is achieved with reactor residence times as low as one minute.

SCWO can handle all types of organic spacecraft waste, in addition to processing condensate, wash, and urine/flush waters. SCWO produces potable water from all input waste waters, creating an entirely potable water supply. The process is not applicable to wastes that are composed primarily of inorganics. SCWO is a safety hazard due to its extremely high operating temperatures and pressures, and it is a corrosive process, presenting material and mechanical reliability problems. A posttreatment is required to handle toxic product gases (such as carbon monoxide). SCWO technology is still under development.

WM - WASTE MANAGEMENT

Baseline Technology

Storage and Biodegradation

- + Very simple and safe technology.
- + Low power consumption.
- High logistics penalties.

Candidate Substitute Technologies

Supercritical Water Oxidation (SCWO)

- + Multifunction technology.
- + Handles a wide variety of organic wastes.
- Posttreatment required to handle toxic gases.
- Safety hazard. Reactor operates at extremely high operating temperature and pressure.
- Corrosive process, presenting material and mechanical reliability problems.
- Consumes O₂.
- Technology requires further development.

Waste Management

Wet Oxidation (WETOX)

Wet oxidation refers to the aqueous phase oxidation of organic materials achieved by interacting air with liquid waste in a high temperature, high pressure (550°F, 2200 psi) reactor. Liquid water catalyzes oxidation, allowing reactions to proceed at temperatures lower than those required for oxidation by open flame combustion. Additionally, water moderates oxidation rates by providing a medium for heat transfer and by removal of excess heat by evaporation. Oxidation products are innocuous, primarily consisting of carbon dioxide and water, although oxidation is not as complete as in the SCWO process. WETOX effluent requires posttreatment by catalytic oxidation and may also require a phase change water recovery system for additional posttreatment. The WETOX process consumes oxygen, is a corrosive process and is a safety hazard due to its high pressure and temperature operation. Research on WETOX recently has centered on industrial applications. Further effort is required to develop a system for space environments.

Waste Management - Water System (WM-WS or RITE)

The WM-WS system recovers water from brine and rejection concentrates generated by other water recovery and waste management technologies. Water recovery from brine reduces the need for water resupply, significantly lowering launch costs. WM-WS uses an evaporator to separate process brine into water vapor and solid waste. The water vapor is catalytically oxidized, then condensed and output to posttreatment. Solid waste is pumped to an incinerator, which produces ash that must be stored and returned to earth. The catalytic oxidizer and incineration units each operate at about 1200°F.

WM-WS with a posttreatment could eventually be used to process all types of space station waste water, replacing all the phase change and non-phase change technologies used on the baseline station. The WM-WS process is not affected by bacteria or particulates, and exterminates microorganisms much more effectively than existing water recovery technologies (TIMES, VCD, RO, MF). The original WM-WS system employed a plutonium heat source, and was known as the Radio Isotope Thermal Energy (RITE) system. WM-WS requires further development.

Electrochemical Decomposition

Electrochemical waste decomposition is a non-thermal electrolysis process where solid organic waste and urine can be degraded by oxidation at the surface of catalytic electrodes. CO₂, N₂, and O₂ are the oxidation products formed at the cell anode, while H₂ is formed at the cathode. Electrochemical decomposition operates at low temperatures (less than 150°F) and oxidizes waste without the consumption of atmospheric oxygen. The process also consumes relatively little power. The electrochemical decomposition system has the disadvantage of being susceptible to carbon monoxide poisoning. Electrochemical decomposition is in the early stages of development.

WM - WASTE MANAGEMENT

Wet Oxidation (WETOX)

- + Handles a wide variety of organic wastes.
- + Oxidation products are innocuous.
- May require extensive posttreatment.
- Safety hazard due to high pressure, high temperature operation.
- Corrosive process.
- Consumes O₂.
- Further development is required for space applications.

Waste Management - Water System (WM-WS or RITE)

- + Water recovery from brines results in large long-term cost savings.
- + More efficient than existing water processors at eliminating bacteria and particulates from waste stream.
- + May become capable of processing all types of space station waste water.
- Requires posttreatment.
- Technology requires further development.

Electrochemical Decomposition

- + High temperatures, pressures not required.
- + Relatively low power consumption.
- + Produces oxygen instead of consuming it.
- Presence of carbon monoxide tends to poison system.
- New technology requiring further development.

TECHNOLOGY SUMMARY

Atmosphere Revitalization (AR):

CO₂ Removal

Four-Bed Molecular Sieve (4BMS)
Solid Amine Water Desorbed (SAWD)
Electrochemical Depolarized Concentrator (EDC)
Air Polarized Concentrator (APC or EDC w,wo/H₂)
Two-Bed Molecular Sieve (2BMS)
Membranes

CO₂ Reduction

Bosch Reactor
Sabatier Reactor
Advanced Carbon Reactor (ACR)
CO₂ Electrolysis

O₂ Generation

Static Feed Water Electrolysis (SFWE)
Liquid Anode Feed Solid Polymer Electrolysis (SPE)
CO₂ Electrolysis
Water Vapor Electrolysis (WVE)

Trace Contaminant Control

Carbon Adsorption Beds with Catalytic Oxidizer
Reactive Bed Plasma (RBP)

Water Recovery and Management (WRM):

Urine Processing

Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES)
Vapor Compression Distillation (VCD)
Air Evaporation System (AES)
Vapor Phase Catalytic Ammonia Removal (VPCAR)

Hygiene Water Processing

Reverse Osmosis (RO)
Multifiltration (MF)

Potable Water Processing

Multifiltration (MF)
Reverse Osmosis (RO)
Electrodeionization

Waste Management (WM):

Storage and Biodegradation
Supercritical Water Oxidation (SCWO)
Wet Oxidation (WETOX)
Waste Management - Water System (WM-WS or RITE)
Electrochemical Decomposition

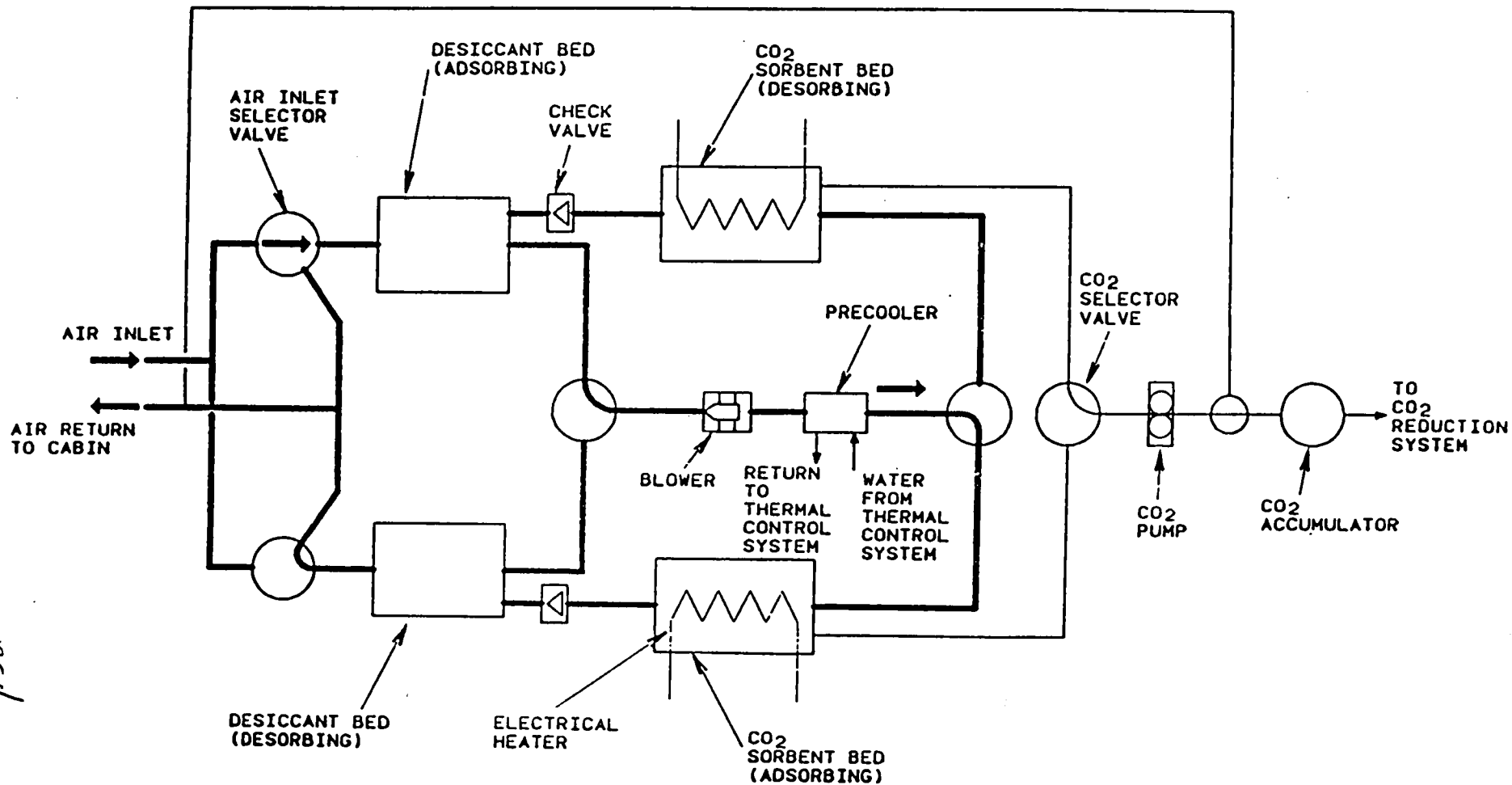
**ECLSS TECHNOLOGY
SCHEMATICS,
PROCESS DIAGRAMS,
AND FLUID INTERFACES**

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CO₂ REMOVAL

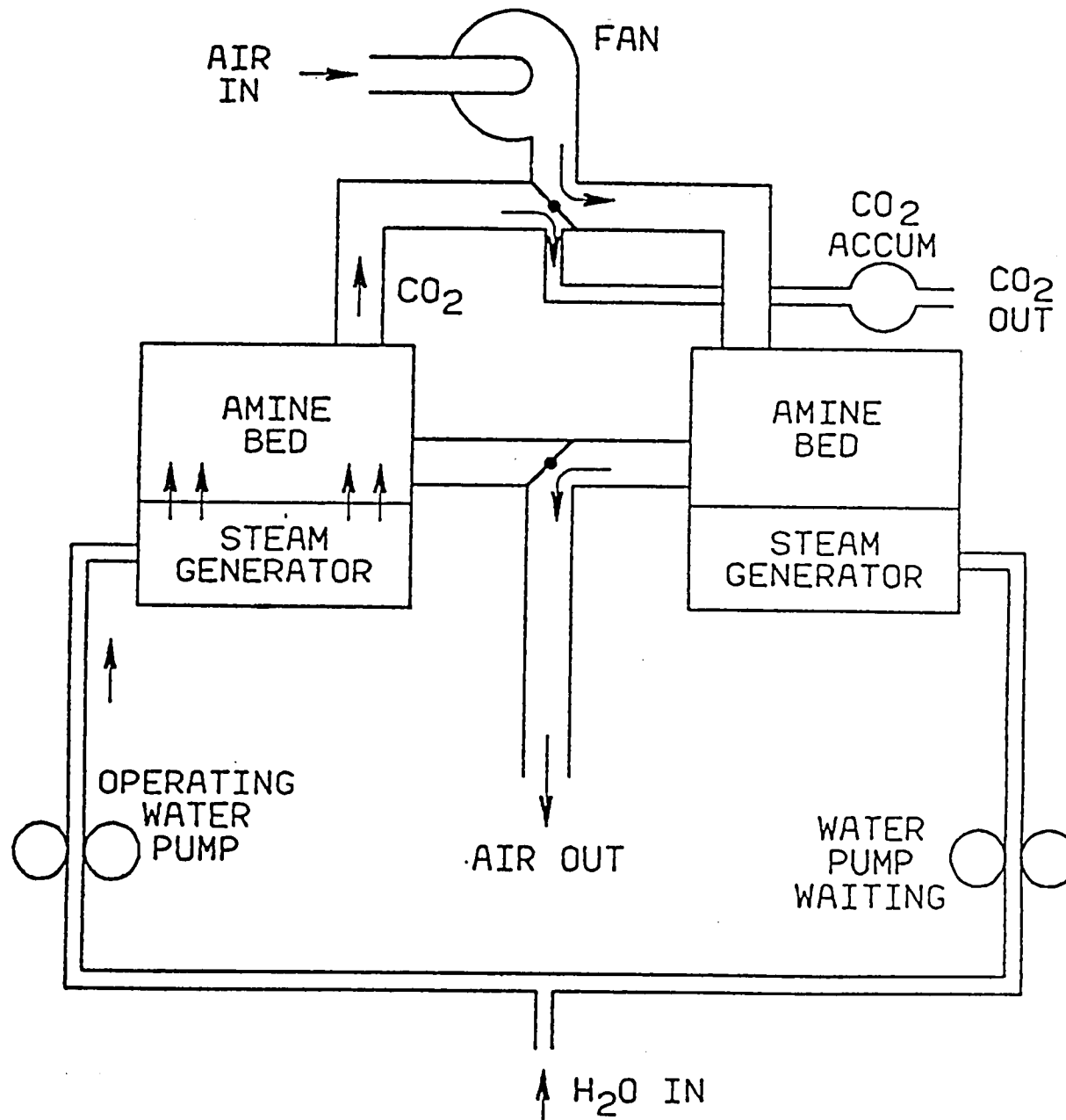


Four-Bed Molecular Sieve System Component Integration

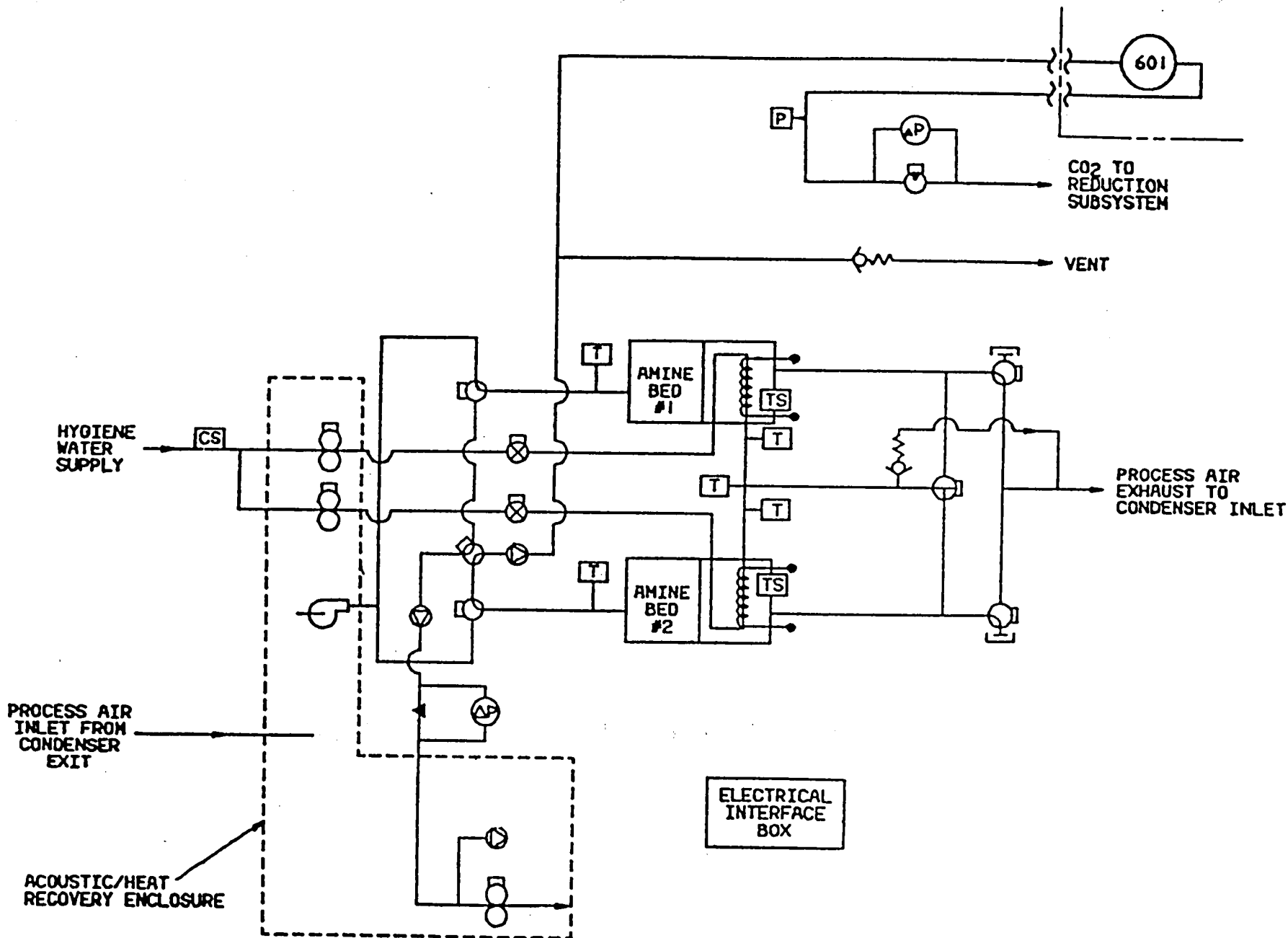
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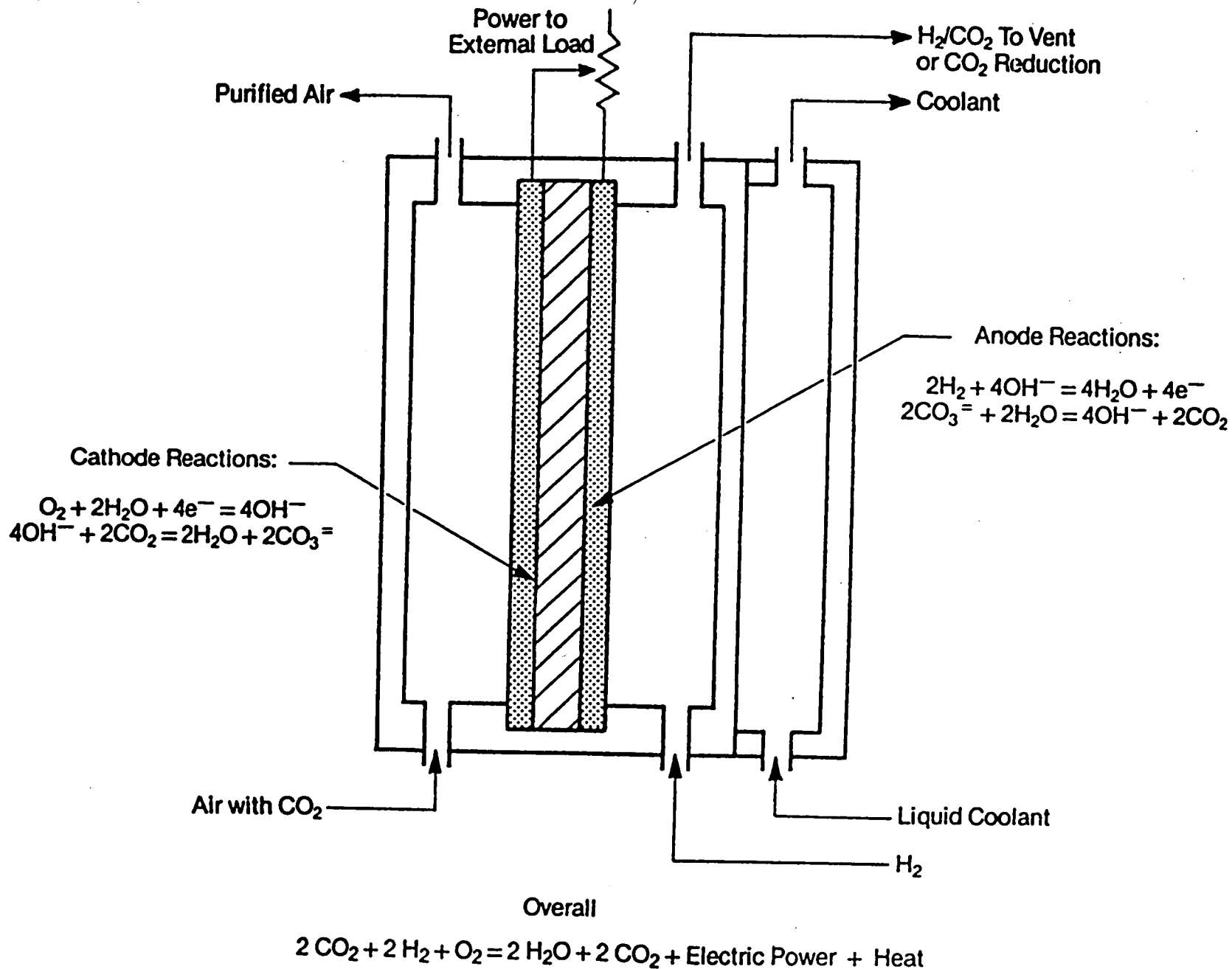


Solid Amine Water Desorbed Process Diagram

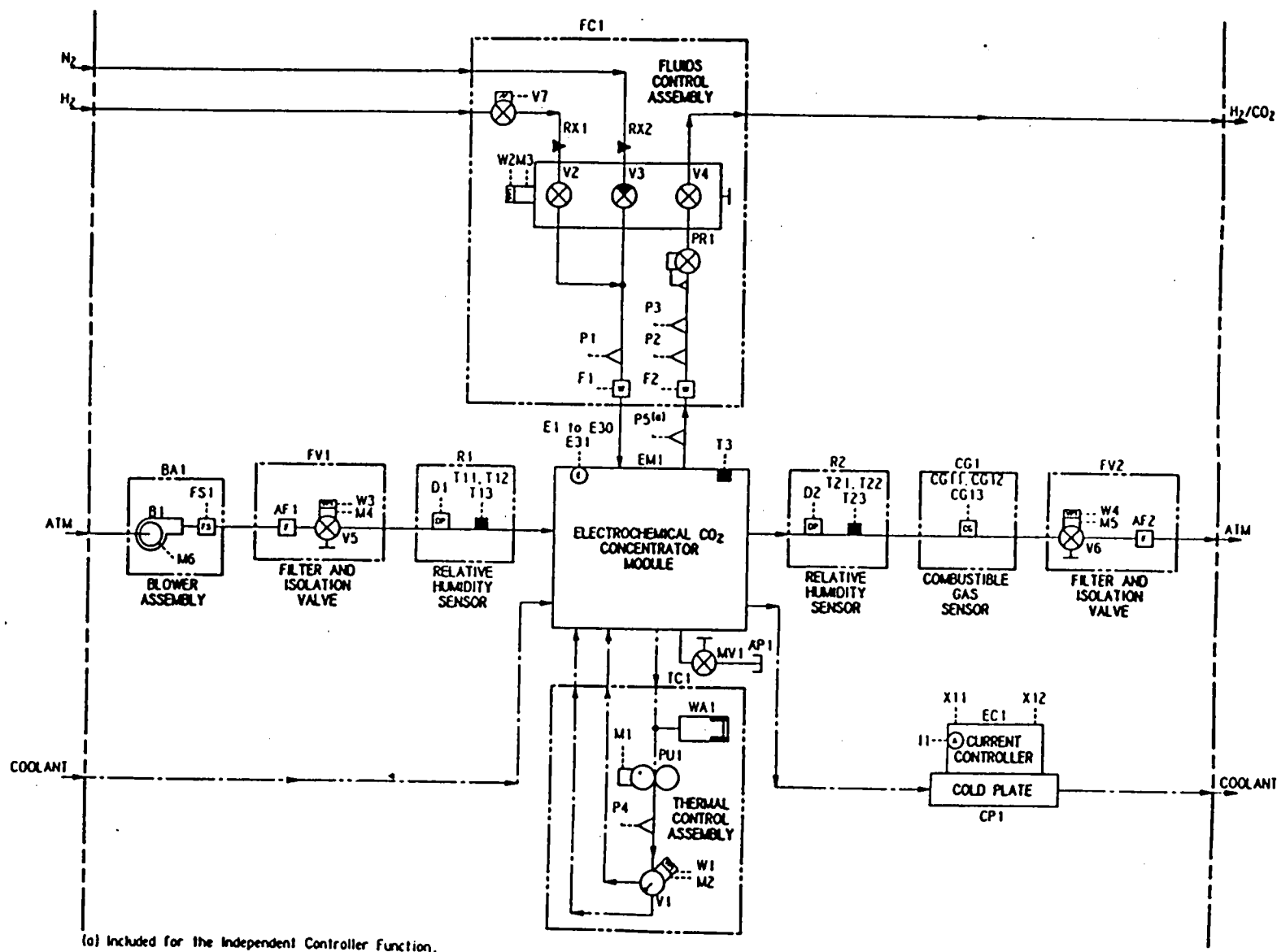


Solid Amine Water Desorbed Mechanical Schematic

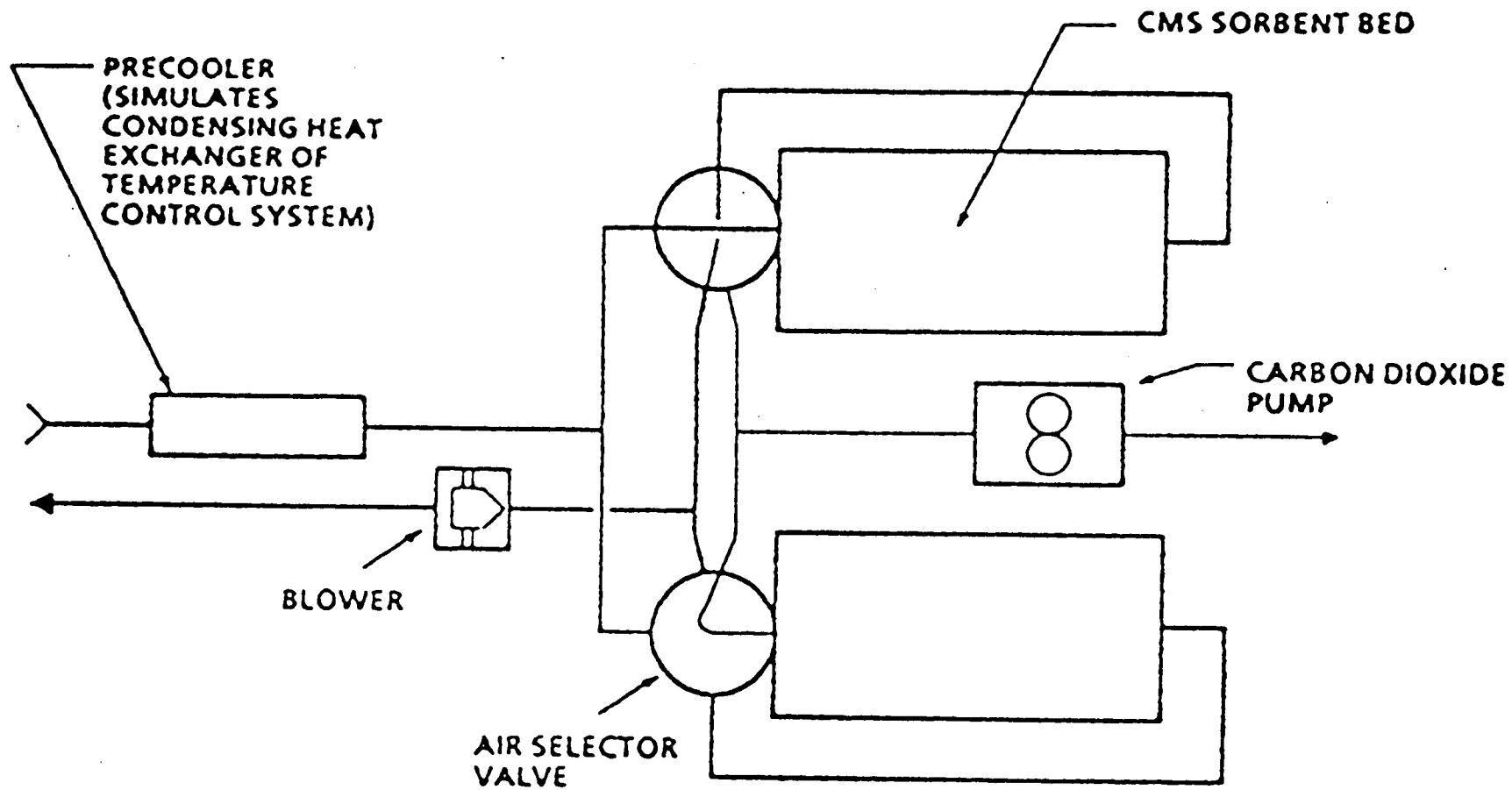
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Electrochemical Depolarized Concentrator Process and Reactions

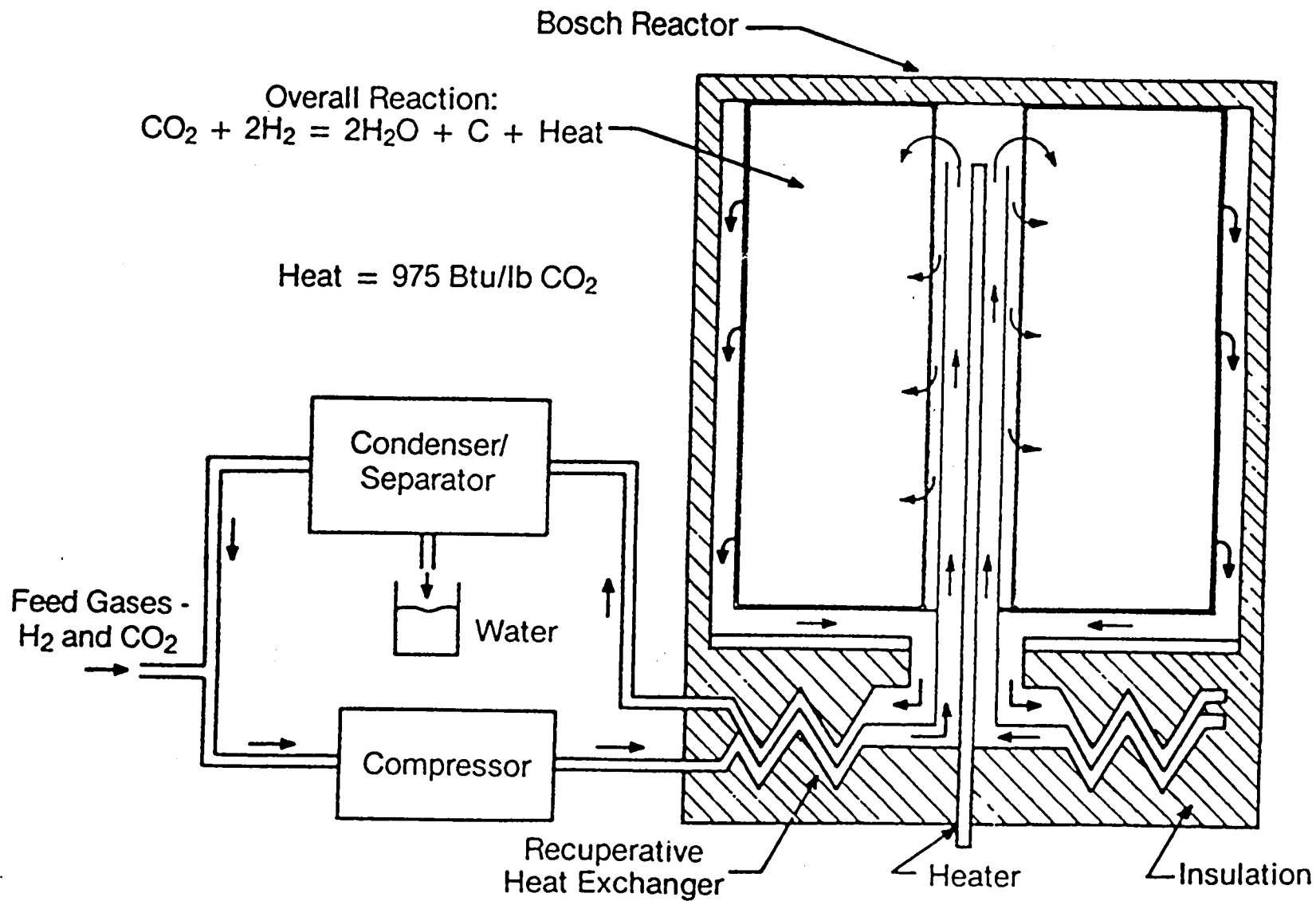


Electrochemical Depolarized Concentrator System Schematic with Sensors

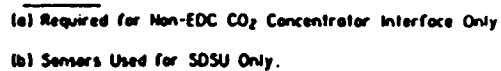


Two-Bed Molecular Sieve Basic Schematic

CO₂ REDUCTION



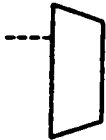



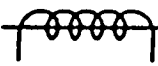















Bosch Process Schematic

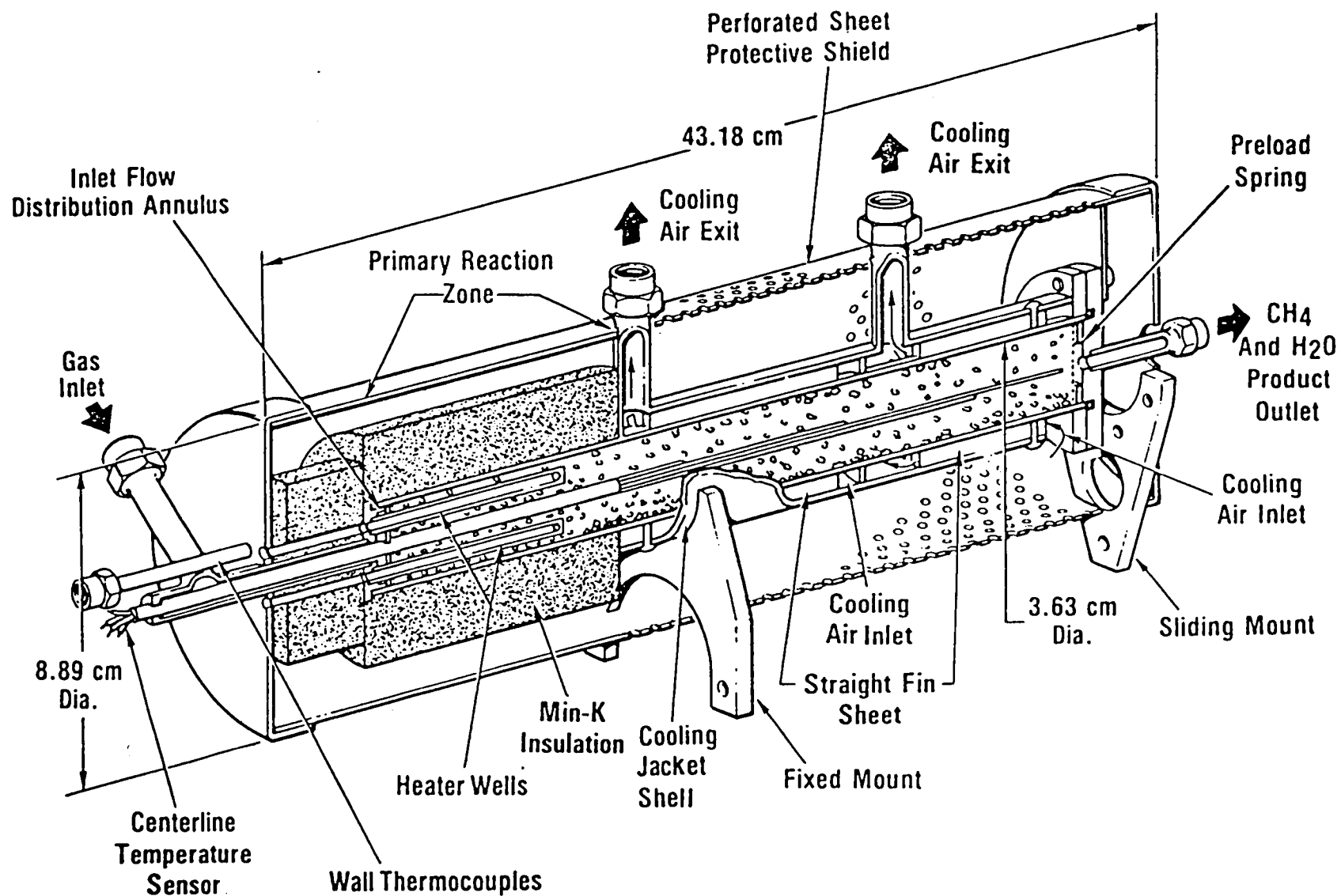


Bosch Mechanical Schematic with Sensors

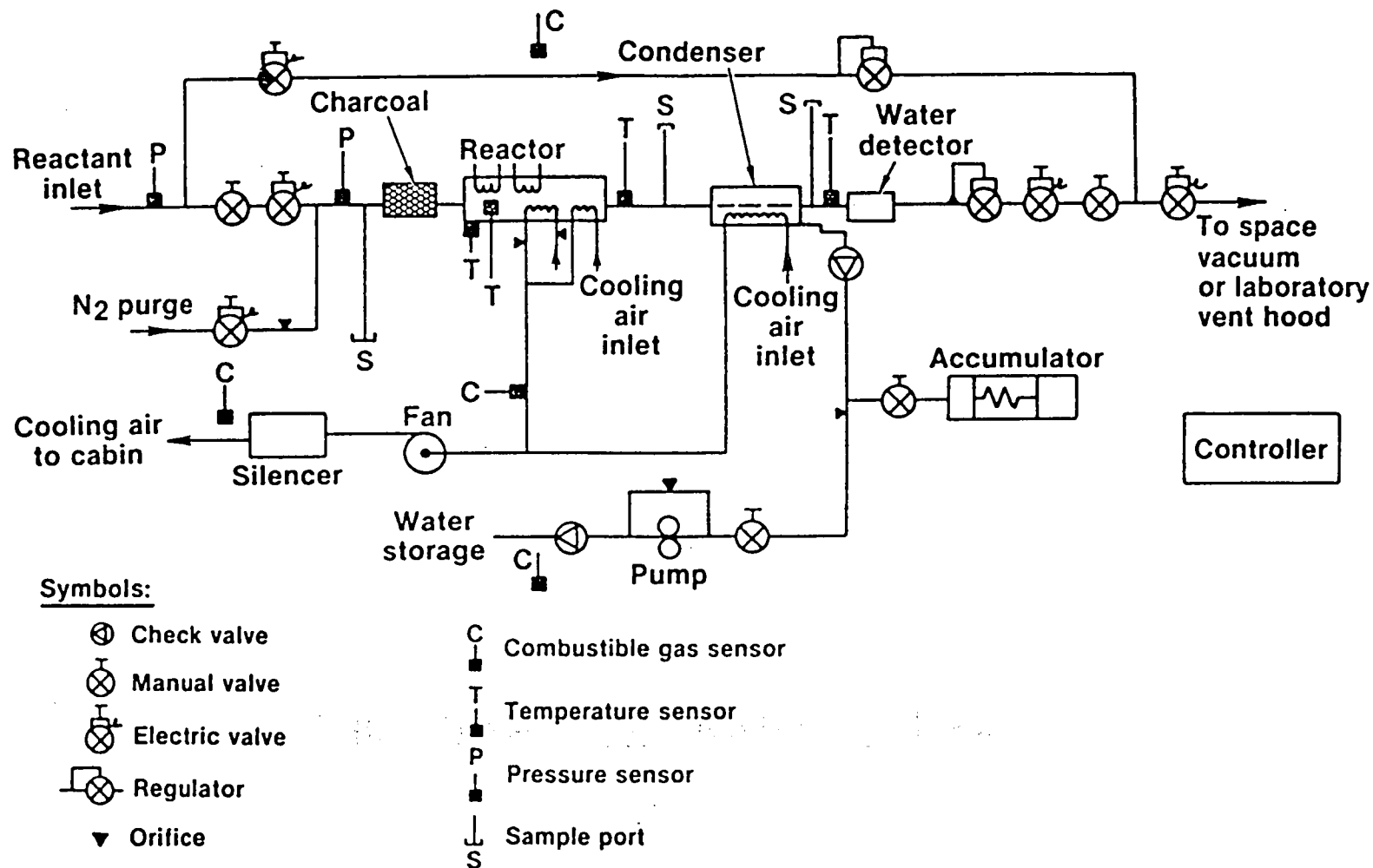
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INTERIOR ONLY

	WATER SEPARATOR		VALVE, MOTOR DRIVEN 4-WAY WITH VALVE POSITION INDICATOR
	COMPRESSOR		VALVE, ELECTRICAL SHUTOFF (N/C) WITH VALVE POSITION INDICATOR
	HEATER, ELECTRICAL		VALVE, ELECTRICAL SHUTOFF (N/C) ENERGIZED OPEN WITH VALVE POSITION INDICATOR
	HEAT EXCHANGER, REGENERATIVE		VALVE, ELECTRICAL SHUTOFF (N/O) DE-ENERGIZED WITH VALVE POSITION INDICATOR
	SAMPLING OR ACCESS PORT, CAPPED		REGULATOR, PRESSURE WITH MANUAL ADJUSTMENT
	SENSOR, PRESSURE		VALVE, RELIEF
	SENSOR, TEMPERATURE		VALVE, CHECK
	SENSOR, COMBUSTIBLE GAS		GAS LINE
	SENSOR, CARBON MONOXIDE		LIQUID LINE
	FILTER		ELECTRICAL LINE

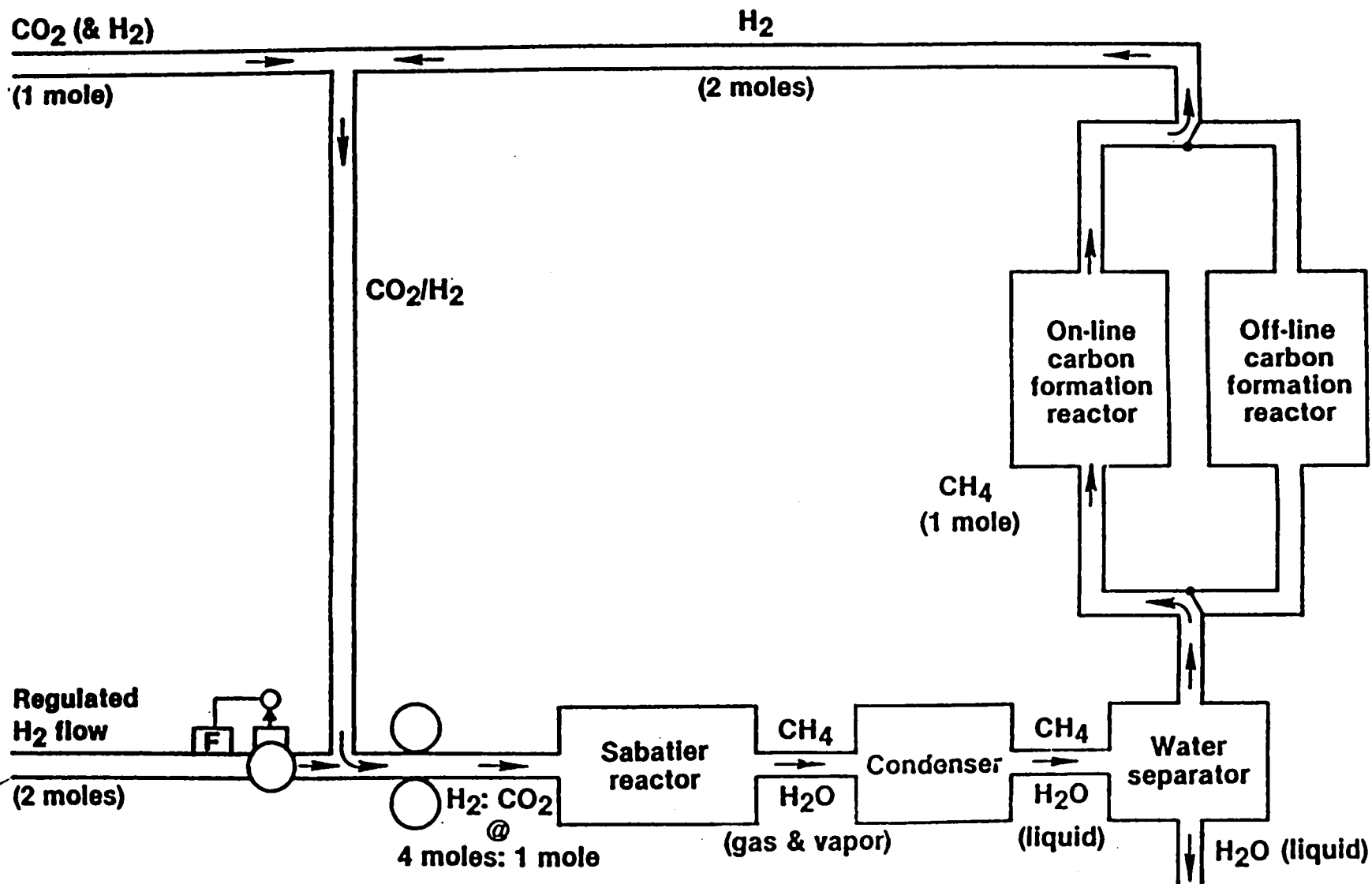
Bosch Schematic Legend



Cross Section of Sabatier Methanation Reactor

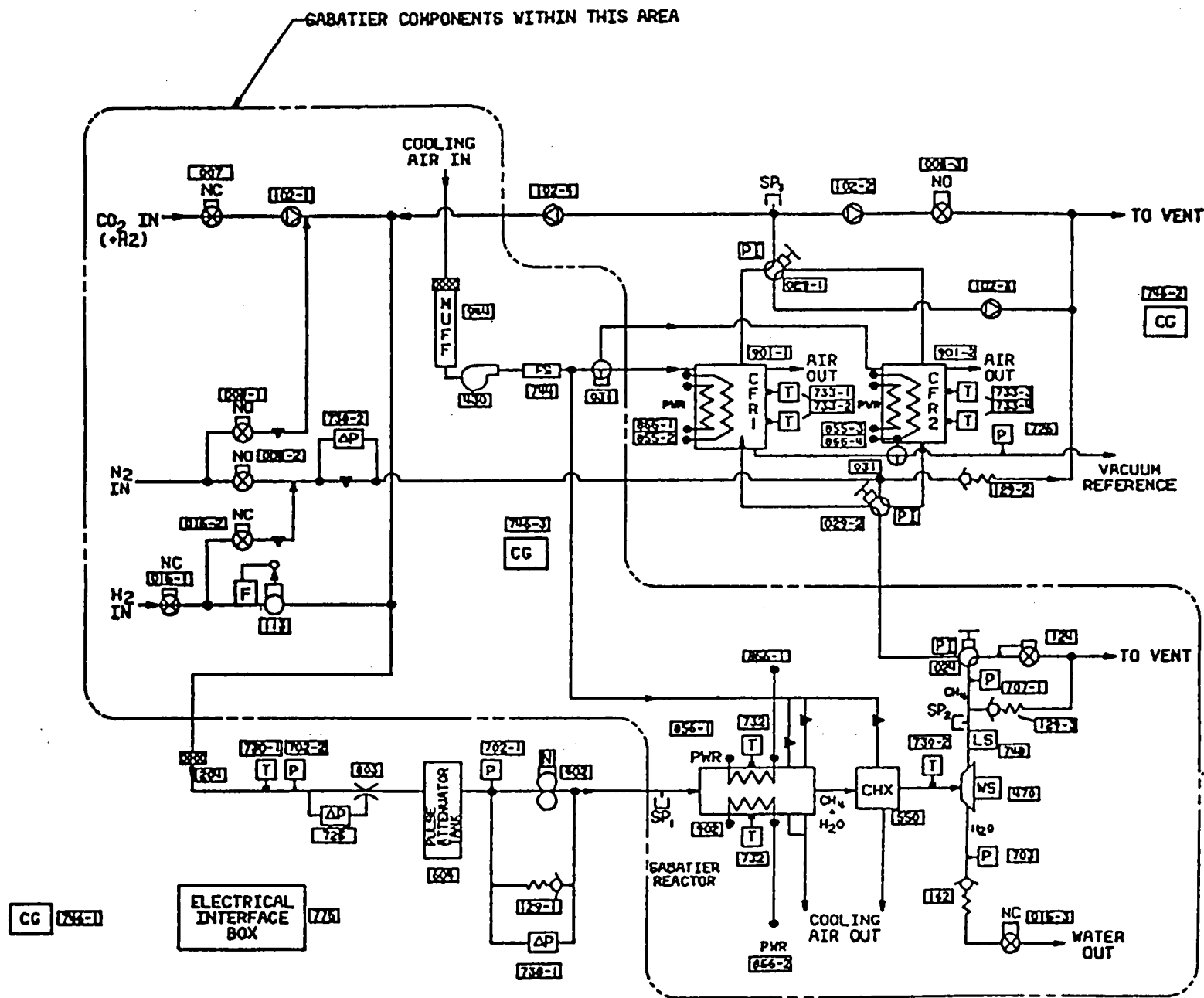


Sabatier System Schematic



Advanced Carbon Reactor Process Schematic

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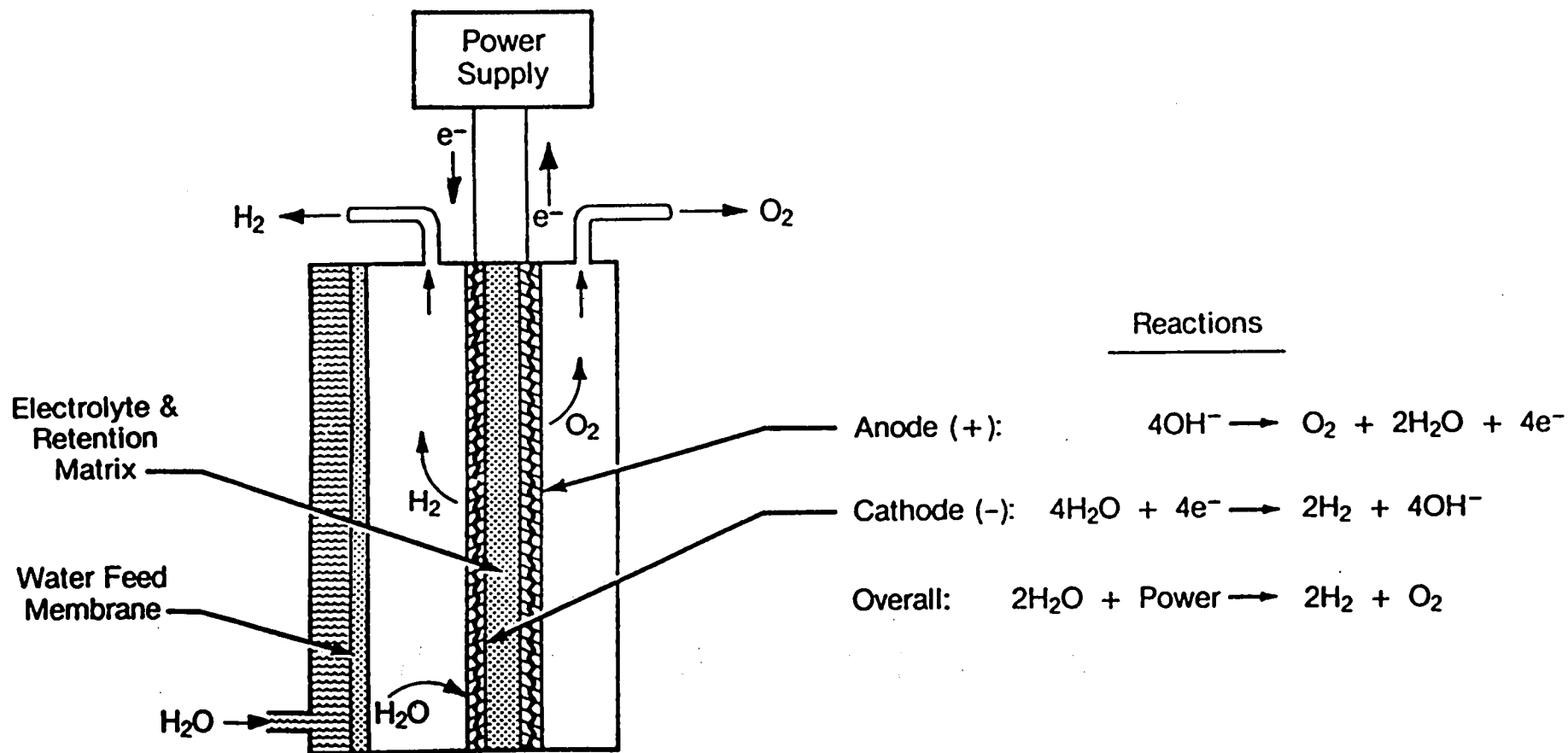
Advanced Carbon Reactor Mechanical Schematic

CO₂ REDUCTION

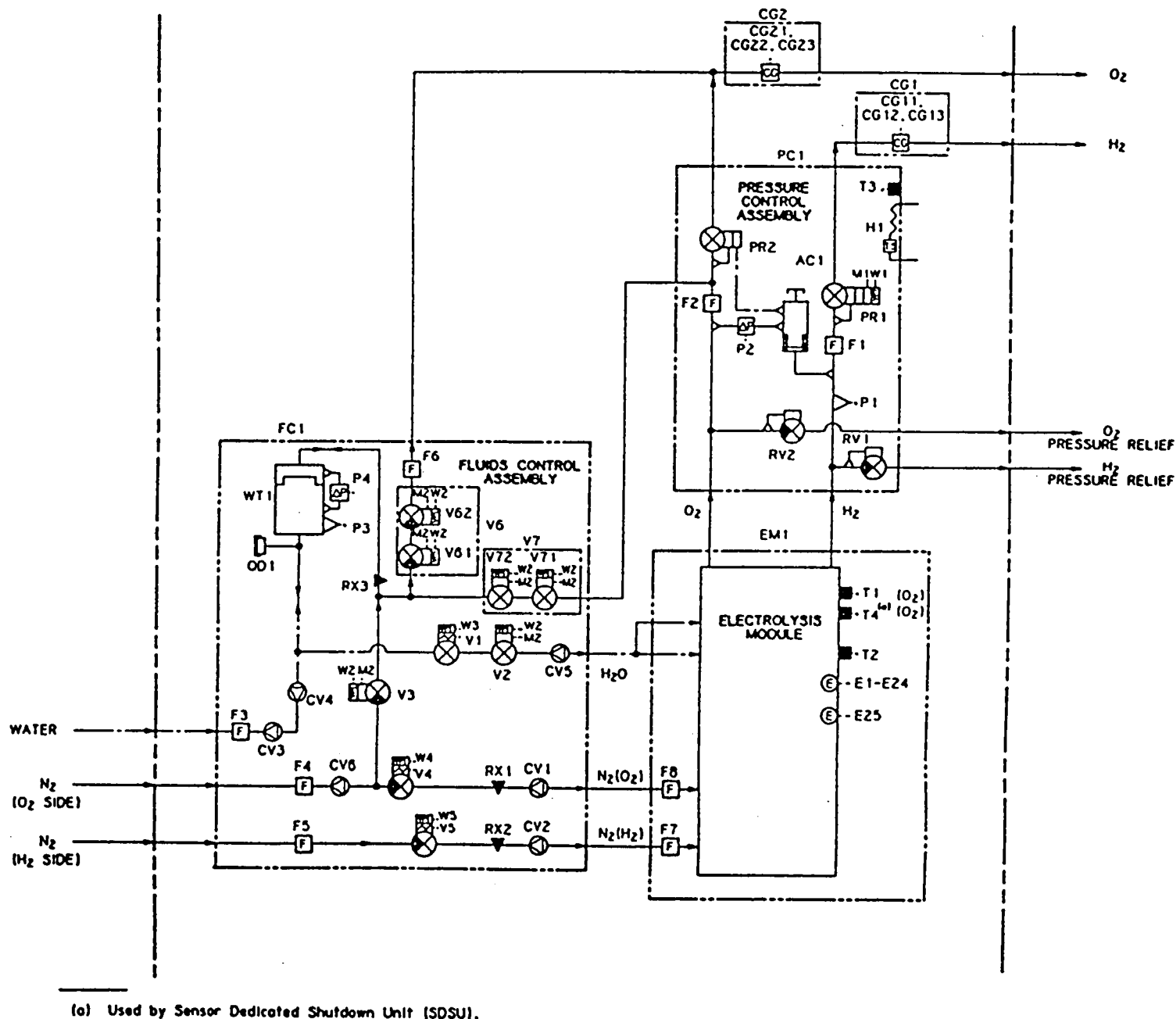
FLUID INTERFACES

TECHNOLOGY	FLUID INTERFACES	
	LINE IN	LINE OUT
Bosch Reactor	Liquid Coolant, H ₂ N ₂ Purge, CO ₂	N ₂ Purge Vent Water to Potable Processor H ₂ Vent Liquid Coolant
Sabatier Reactor	CO ₂ , H ₂ Avionics Air	Water to Potable Processor Vent to Storage Avionics Air
Advanced Carbon Reactor	CO ₂ , H ₂ Avionics Air, N ₂	Water to Potable Processor Avionics Air N ₂ Purge Vent, H ₂ Vent Vacuum (for vacuum jacket)
CO ₂ Electrolysis	CO ₂ , N ₂ Avionics Air	O ₂ , H ₂ Vent CO/CO ₂ to Carbon Deposition Reactor Avionics Air

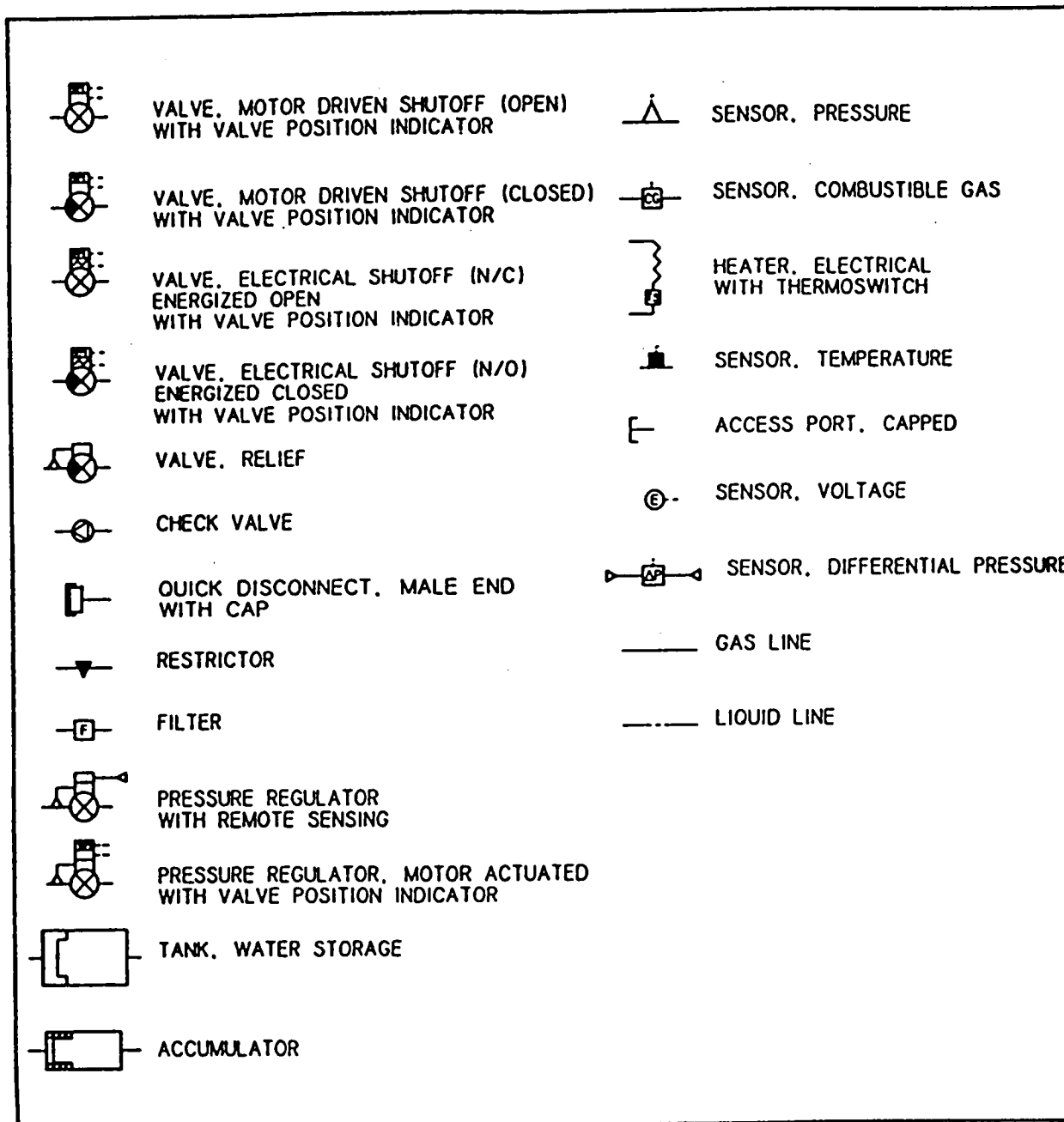
O₂ GENERATION



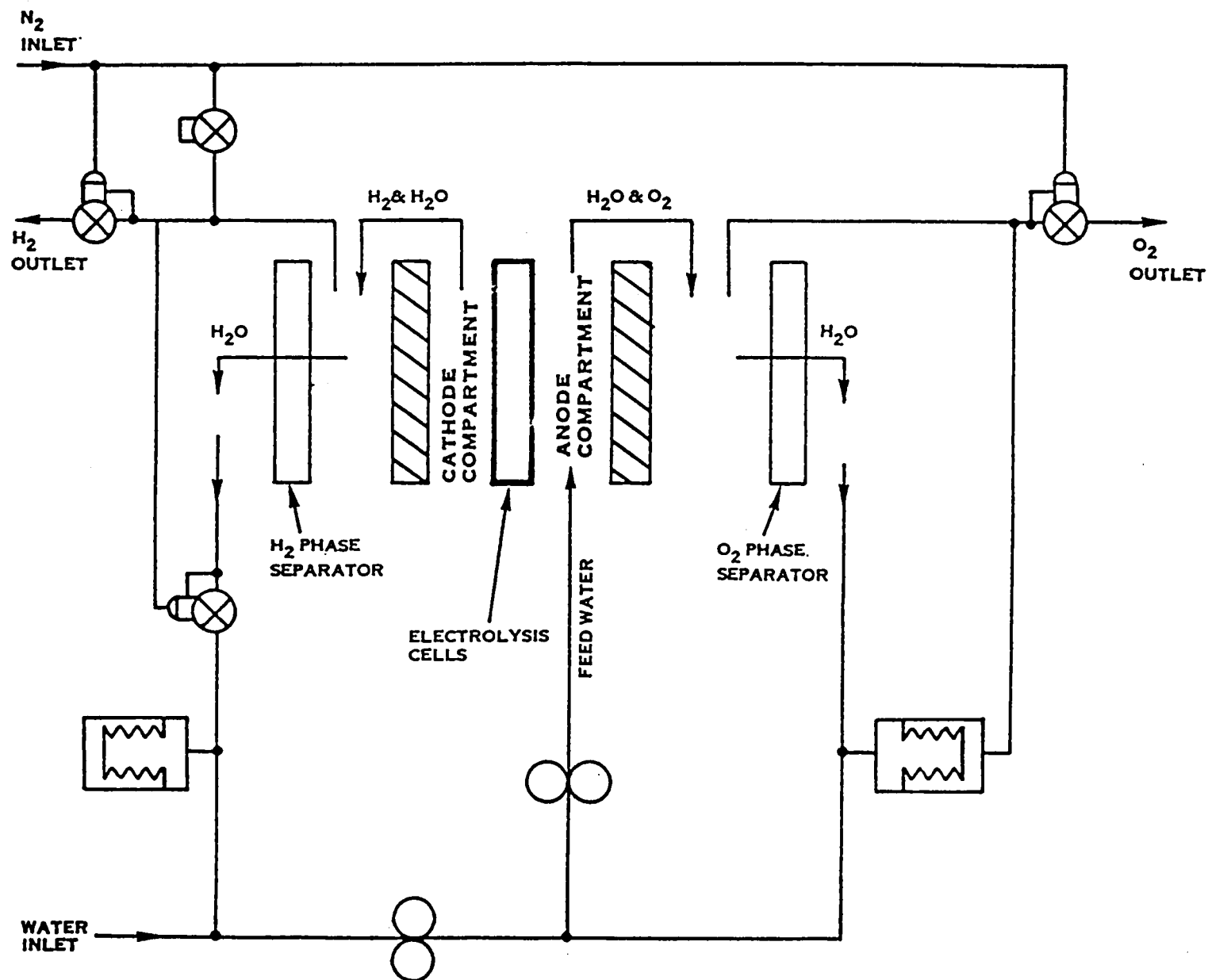
Static Feed Water Electrolysis Cell and Reactions



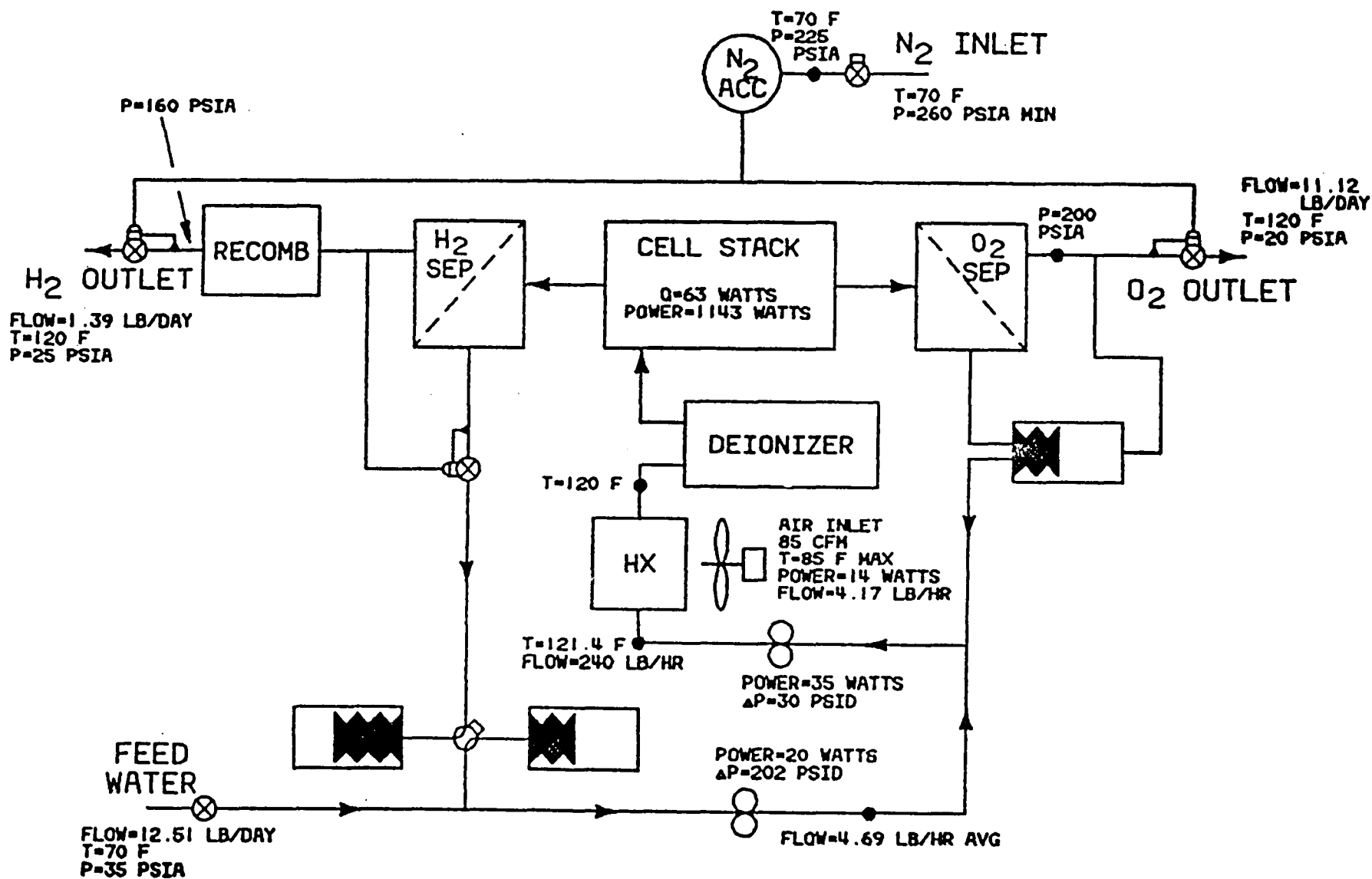
Static Feed Water Electrolysis Mechanical Schematic



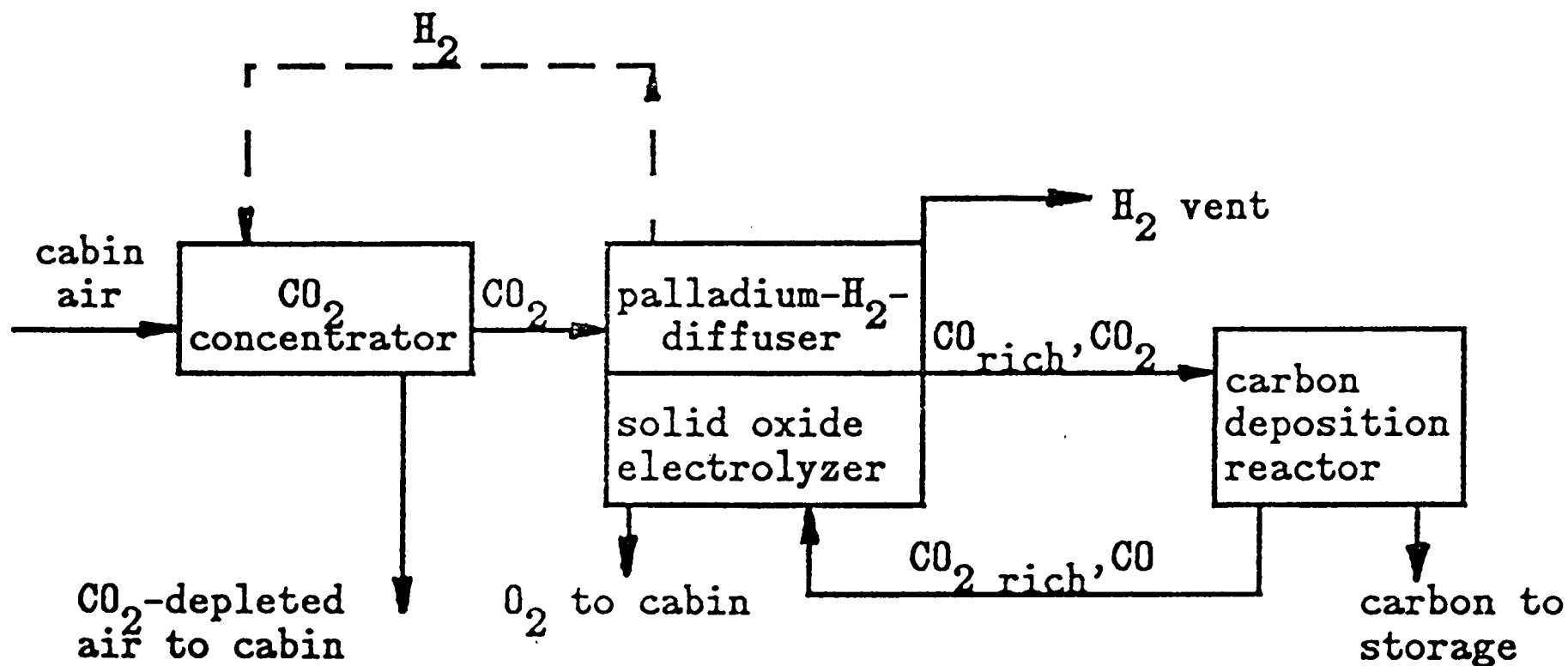
Static Feed Water Electrolysis Schematic Legend



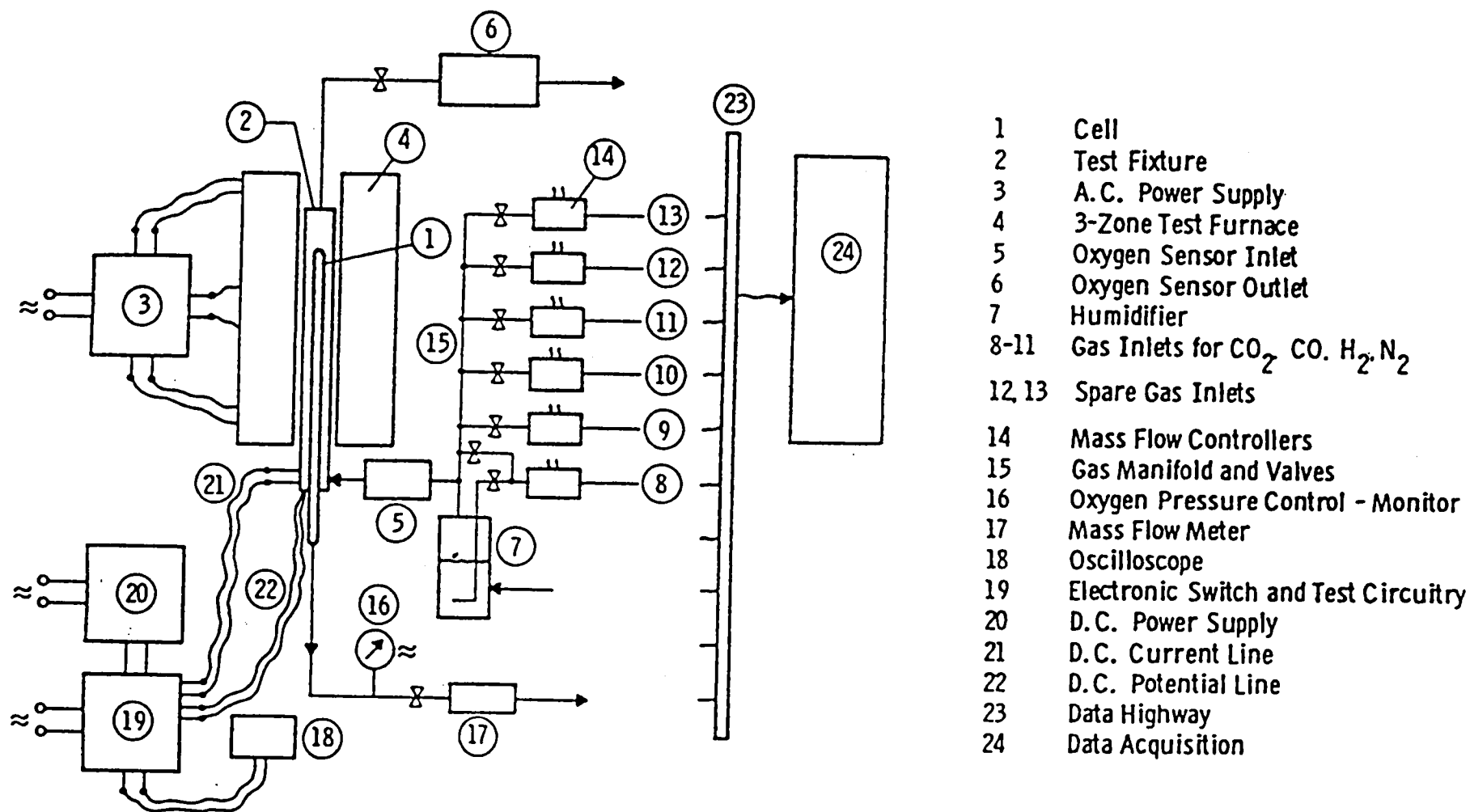
Liquid Anode Feed Solid Polymer Electrolysis Simplified Schematic



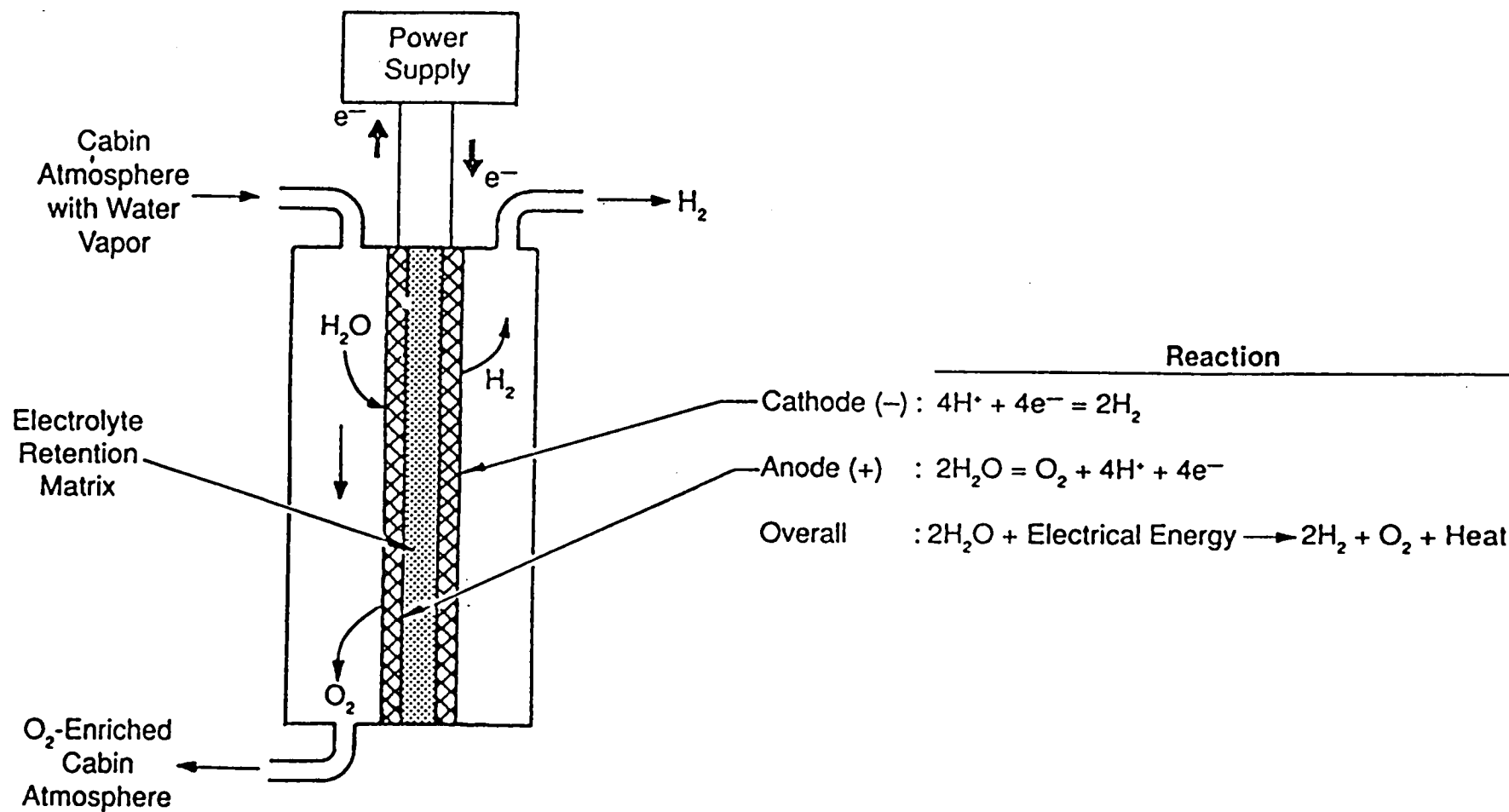
Liquid Anode Feed Solid Polymer Electrolysis Flow Chart



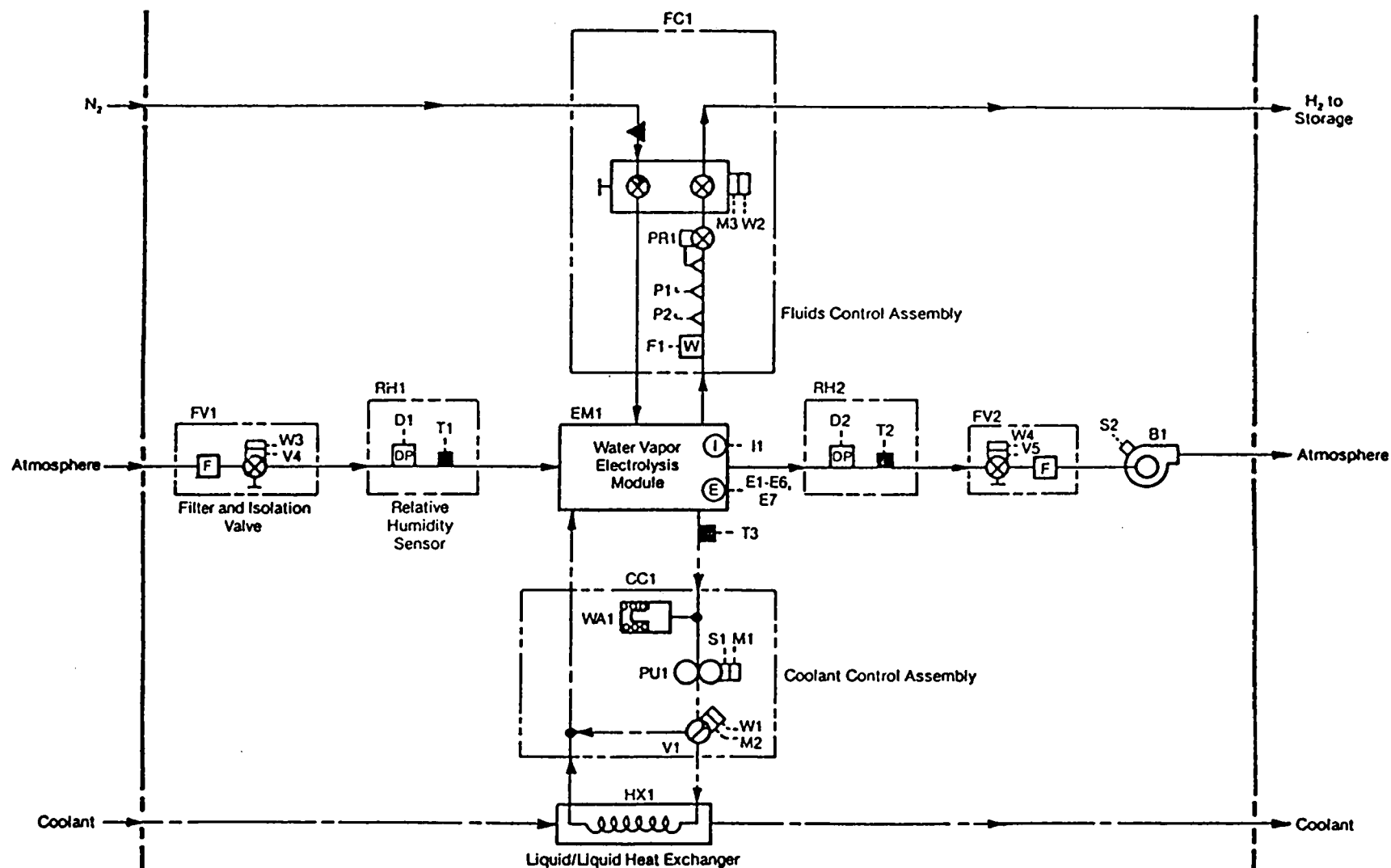
Advanced Concept Oxygen Reclamation Scheme Using CO₂ Electrolysis



Essential Components of a Breadboard CO₂ Electrolysis Unit



Water Vapor Electrolysis Cell and Reactions



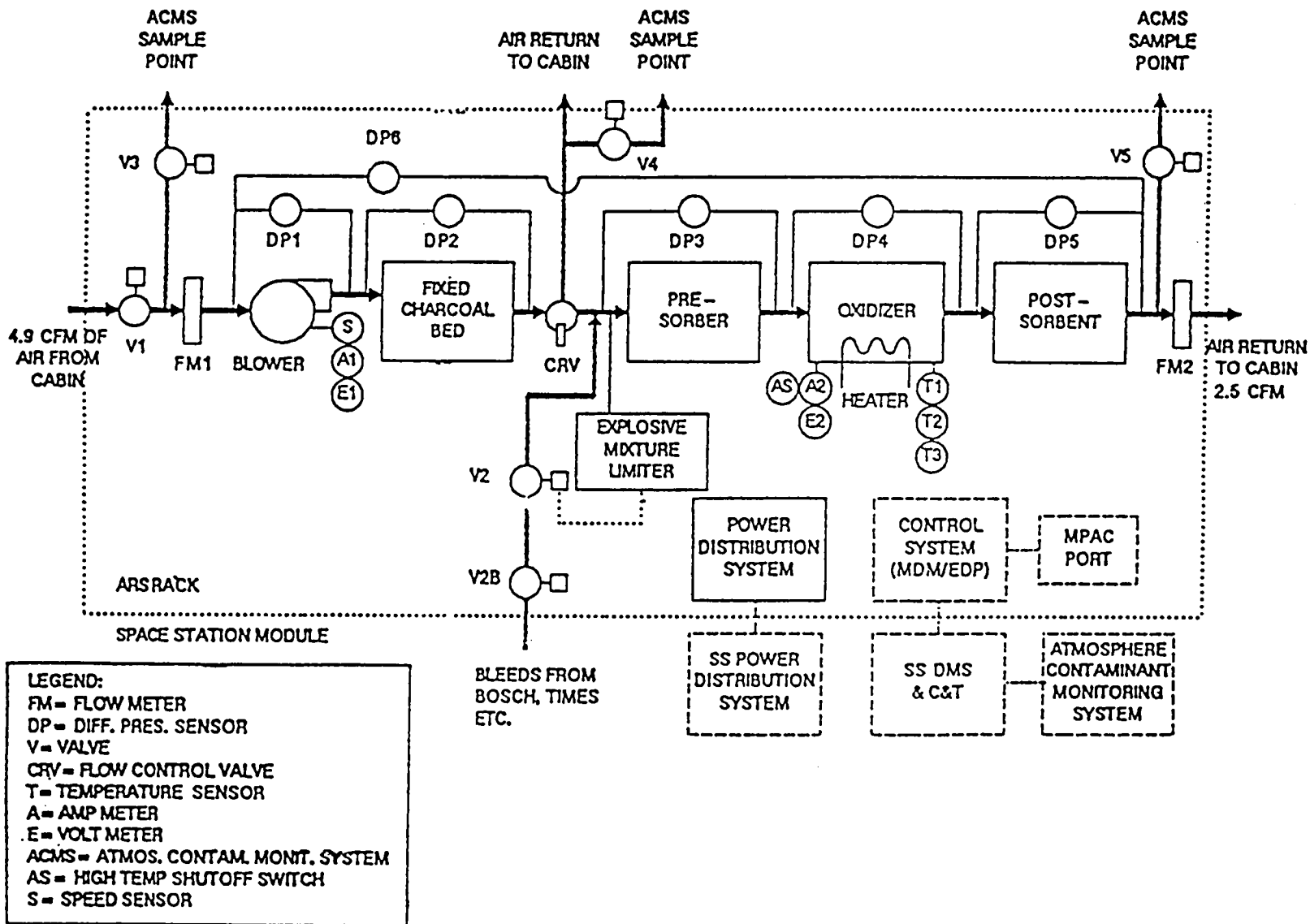
Water Vapor Electrolysis Mechanical Schematic with Sensors

O₂ GENERATION

FLUID INTERFACES

TECHNOLOGY	FLUID INTERFACES	
	LINE IN	LINE OUT
Static Feed Water Electrolysis	Hygiene Water N ₂ (O ₂ Side) N ₂ (H ₂ Side)	O ₂ , H ₂
Liquid Anode Feed Solid Polymer Electrolysis	Hygiene Water N ₂ , Avionics Air	O ₂ , H ₂ Avionics Air
Water Vapor Electrolysis	Cabin Air Liquid Coolant	Return Air, H ₂ , Liquid Coolant
CO ₂ Electrolysis	See CO ₂ Reduction	

TRACE CONTAMINANT CONTROL



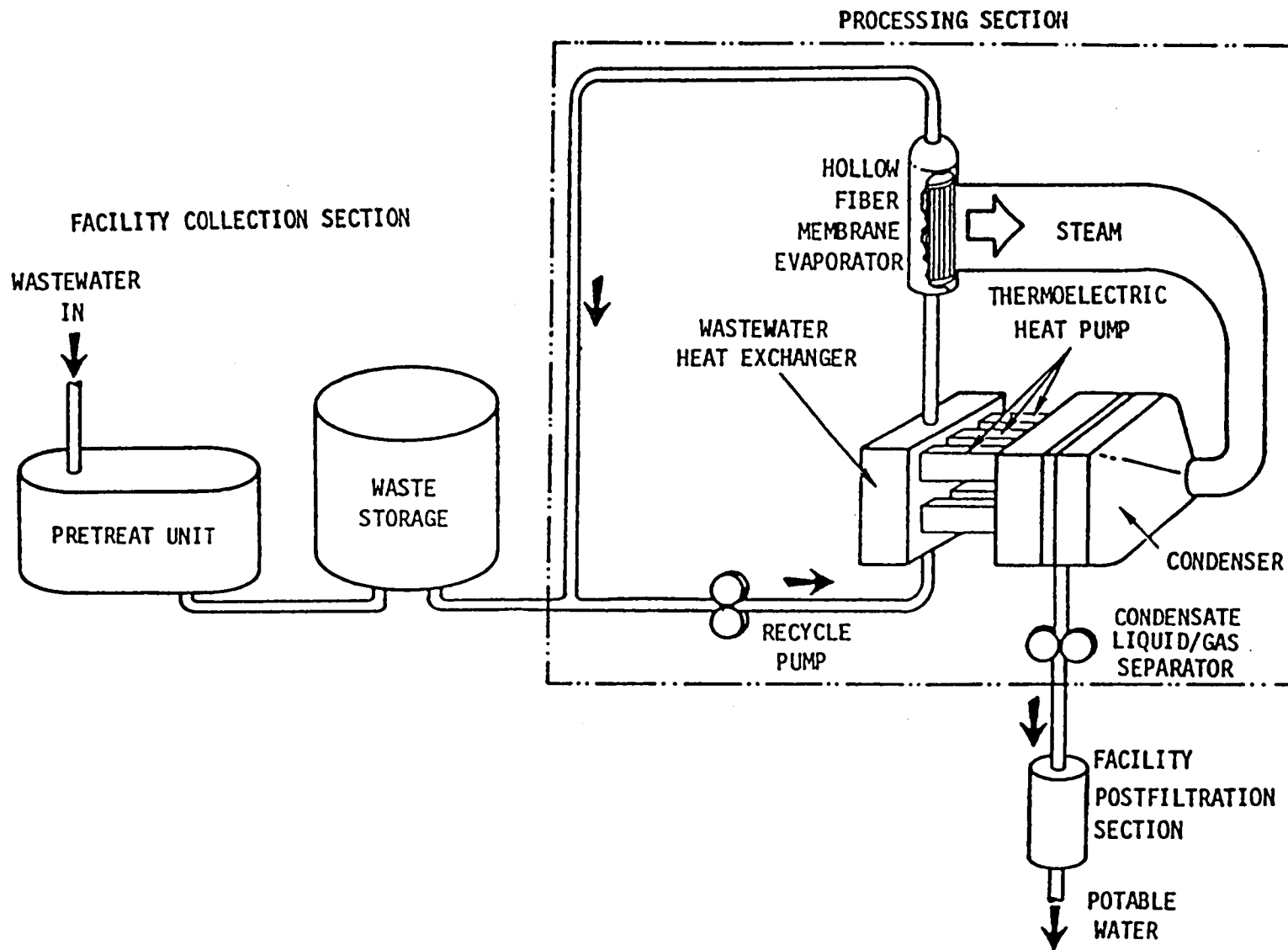
Baselined Trace Contaminant Control System Schematic

TRACE CONTAMINANT CONTROL

FLUID INTERFACES

TECHNOLOGY	FLUID INTERFACES	
	LINE IN	LINE OUT
Expendable Carbon Beds with Catalytic Oxidizer	Cabin Air Avionics Air	Return Air Avionics Air
Reactive Bed Plasma	Cabin Air	Return Air

URINE PROCESSING

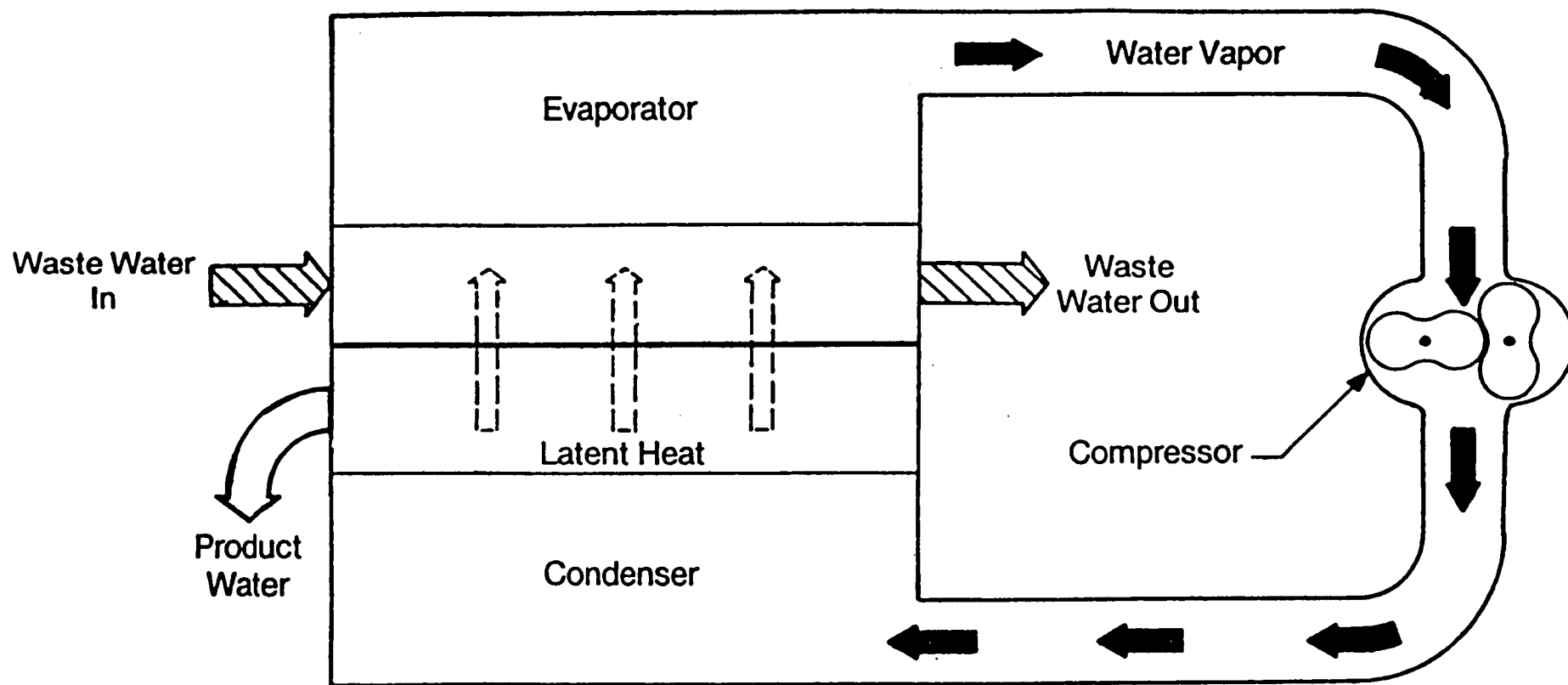


Thermoelectric Integrated Membrane Subsystem Process Schematic

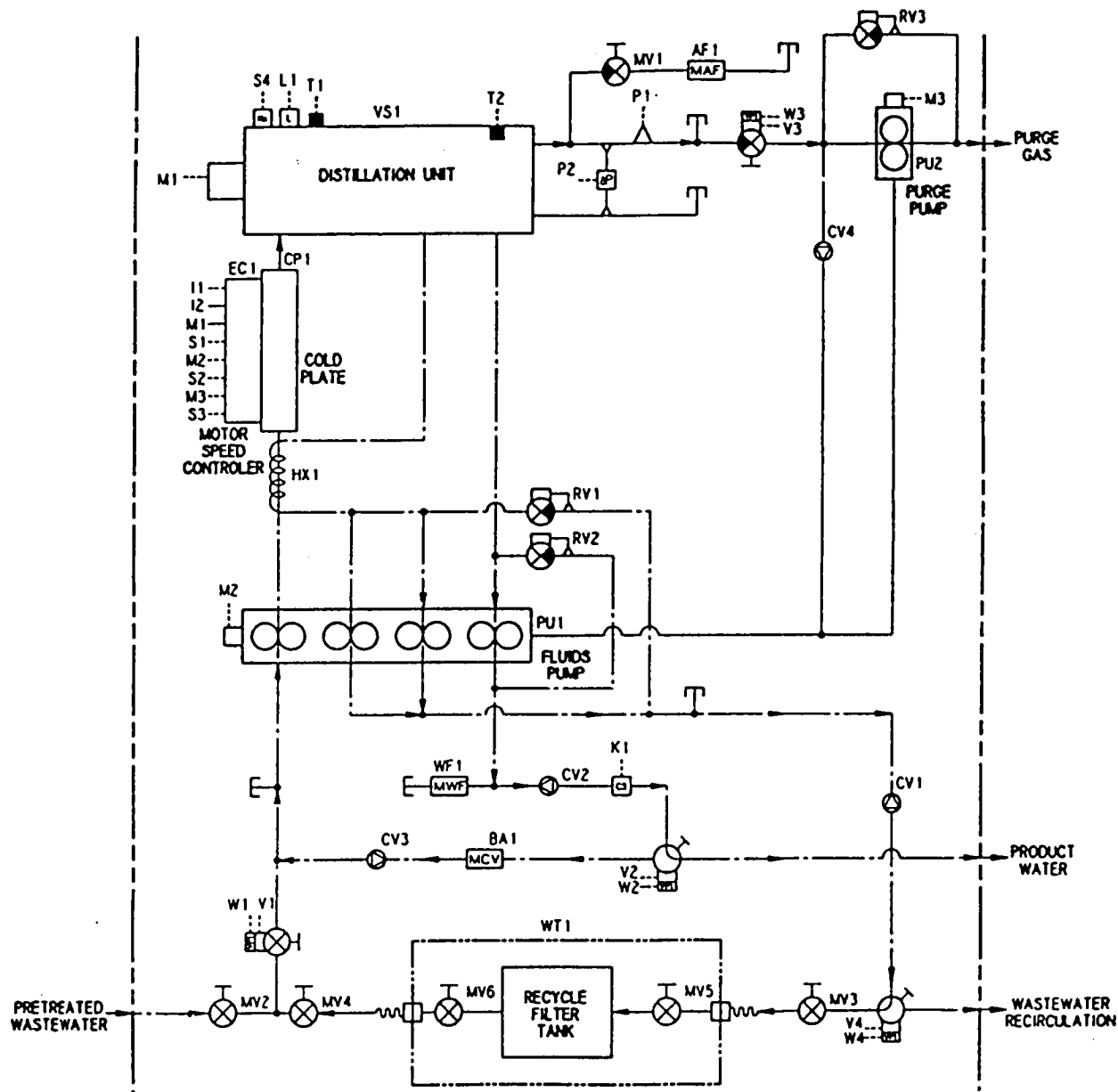
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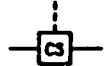


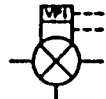







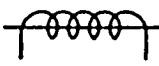
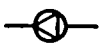



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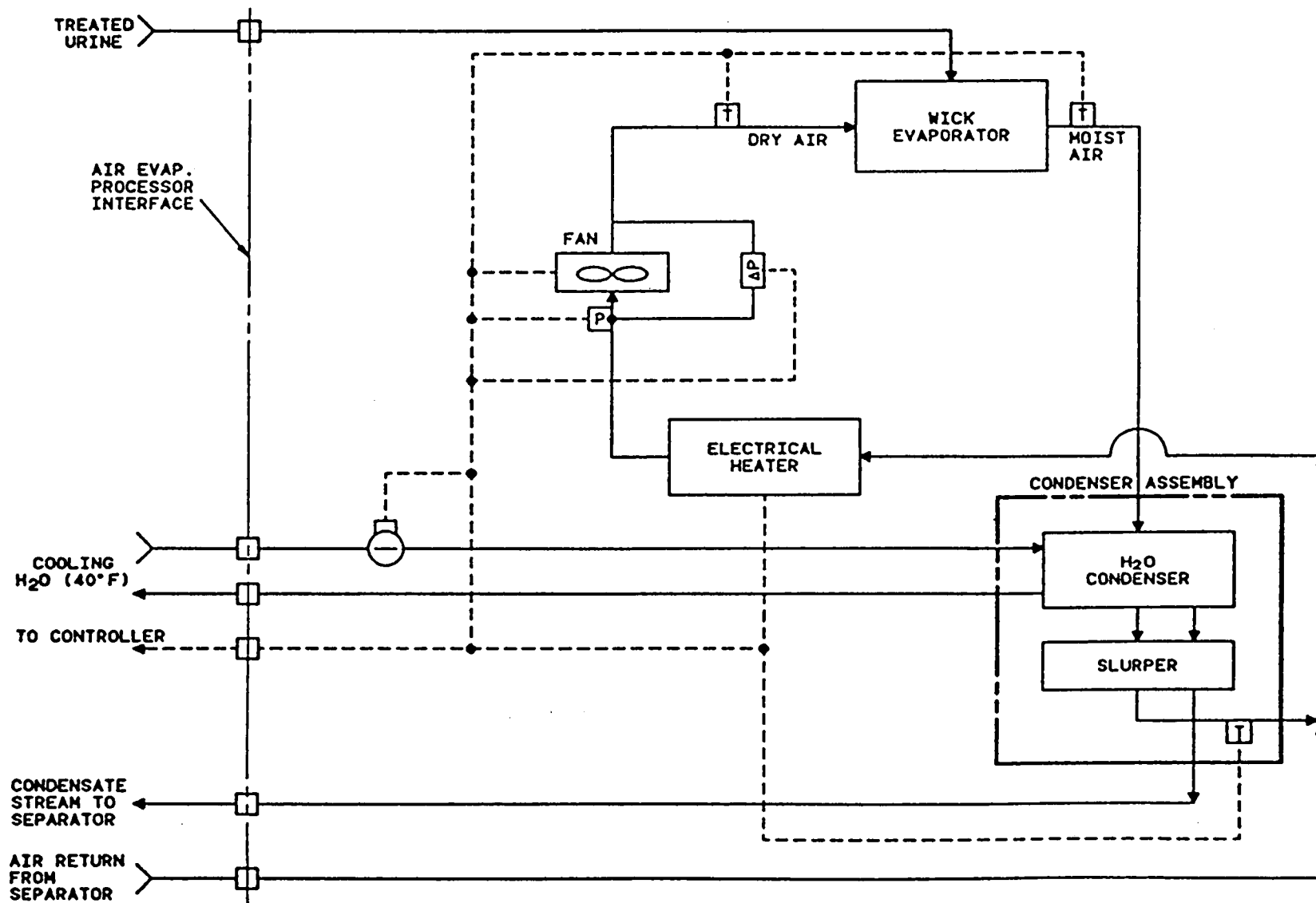
Vapor Compression Distillation Process Schematic



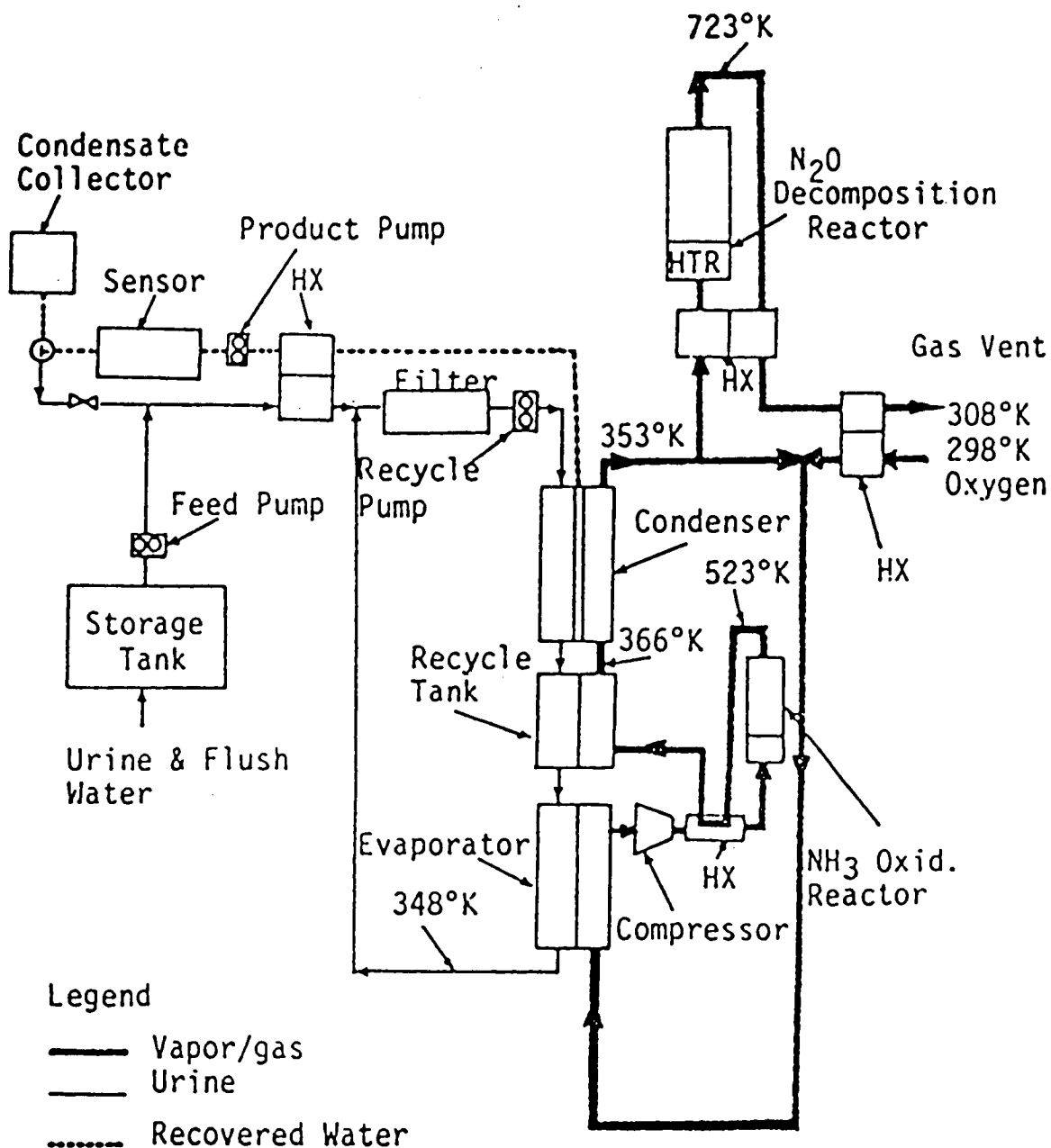
Vapor Compression Distillation Mechanical Schematic

	MOTOR ACTUATOR		MICROBIAL AIR FILTER
	SAMPLING OR ACCESS PORT, CAPPED		VALVE, MICROBIAL CHECK
	SENSOR, CONDUCTIVITY		VALVE, MOTOR DRIVEN NORMALLY CLOSED WITH MANUAL OVERRIDE AND VALVE POSITION INDICATOR
	SENSOR, DIFFERENTIAL PRESSURE		VALVE, MOTOR DRIVEN NORMALLY OPEN WITH MANUAL OVERRIDE AND VALVE POSITION INDICATOR
	SENSOR, LIQUID		VALVE, THREE-WAY MOTOR DRIVEN WITH MANUAL OVERRIDE AND VALVE POSITION INDICATOR
	SENSOR, PRESSURE		VALVE, MANUAL SHUTOFF NORMALLY OPEN
	SENSOR, SPEED		VALVE, MANUAL SHUTOFF NORMALLY CLOSED
	SENSOR, TEMPERATURE		HEAT EXCHANGER, REGENERATIVE
	VALVE, CHECK		VALVE, RELIEF
	COUPLING, QUICK DISCONNECT		HOSE, FLEXIBLE

Vapor Compression Distillation Schematic Legend



Air Evaporation System Schematic



Vapor Phase Catalytic Ammonia Removal Flow Schematic

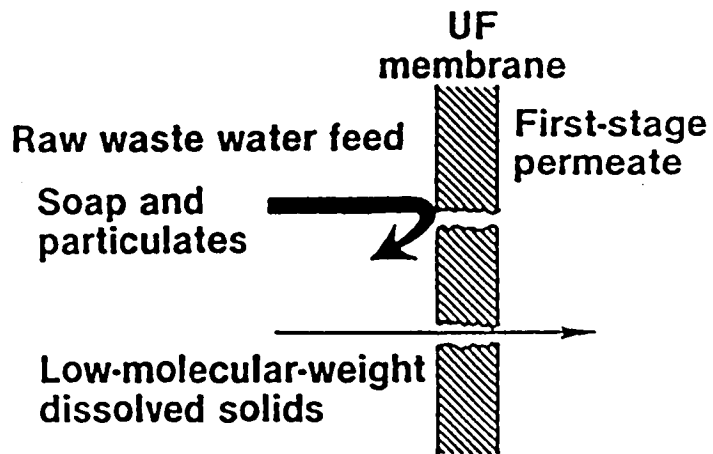
URINE PROCESSING

FLUID INTERFACES

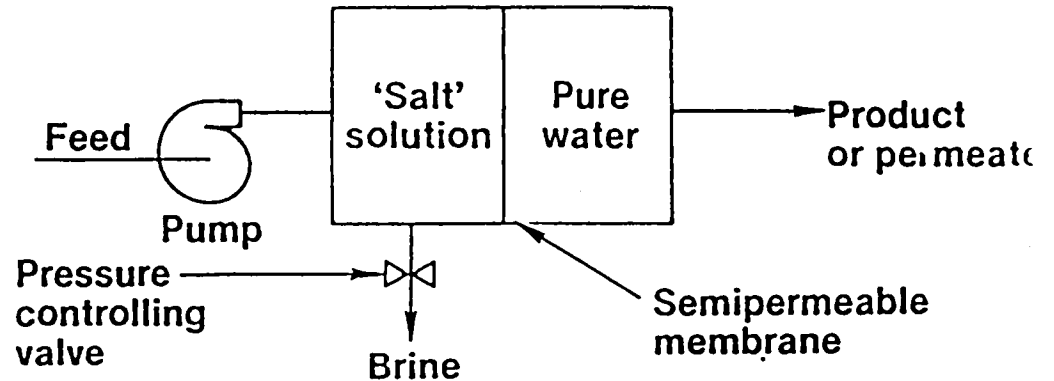
TECHNOLOGY	FLUID INTERFACES	
	LINE IN	LINE OUT
Thermoelectric Integrated Membrane Evaporation Subsystem	Pretreated Urine/Flush Water Avionics Air	Water to Hygiene Processor Brine, Vent Avionics Air
Vapor Compression Distillation	Pretreated Urine/Flush Water	Water to Hygiene Processor Brine, Vent
Vapor Phase Catalytic Ammonia Removal	Untreated Urine/Flush Water O ₂ , Cabin Air Liquid Coolant	Water to Potable Processor, Vent Liquid Coolant
Air Evaporation System	Pretreated Urine/Flush Water Liquid Coolant	Water to Hygiene Processor Liquid Coolant Return Air from Separator

HYGIENE WATER PROCESSING

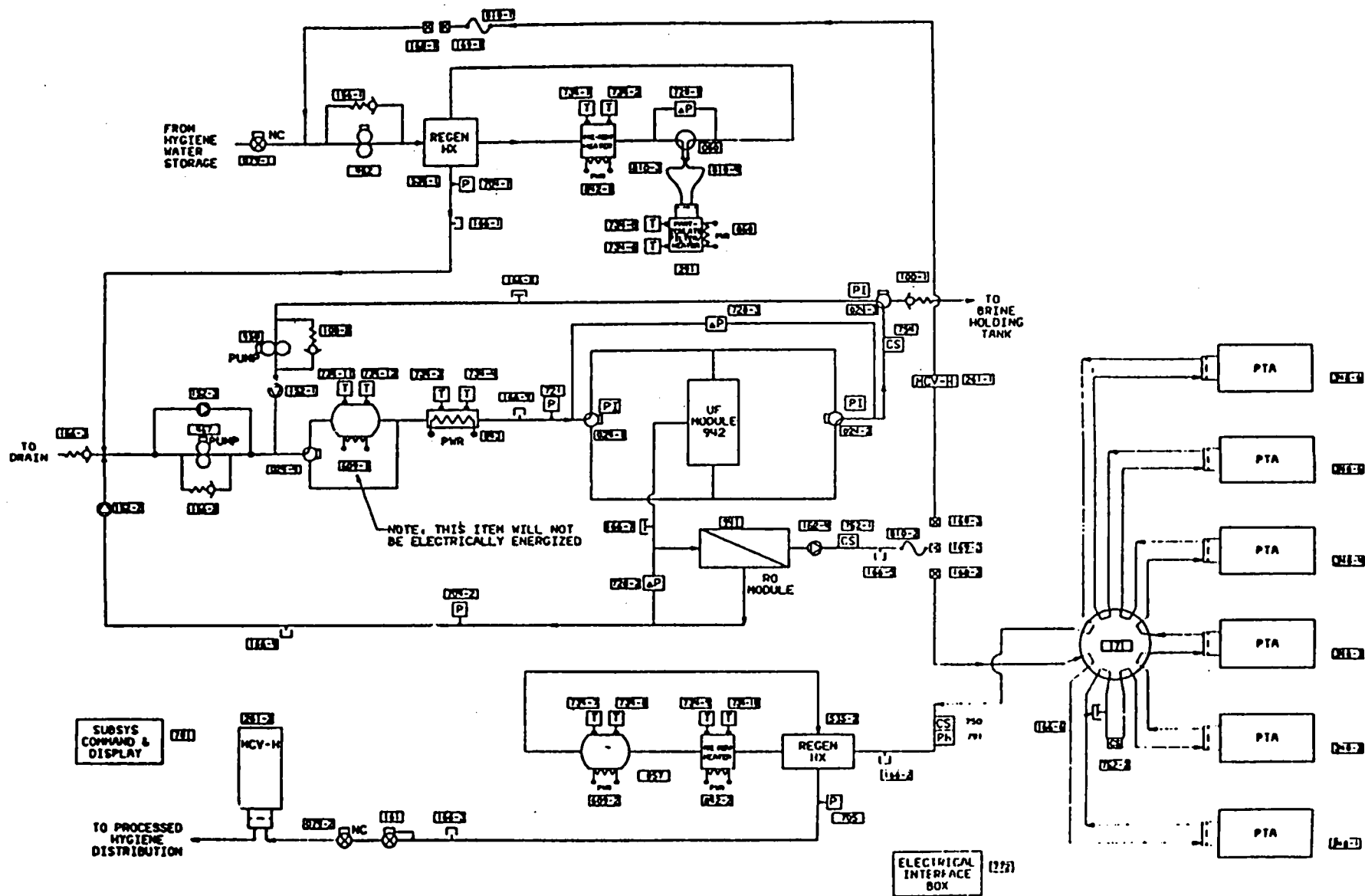
Ultrafiltration



Reverse Osmosis



General Operating Characteristics of Ultrafiltration and Reverse Osmosis



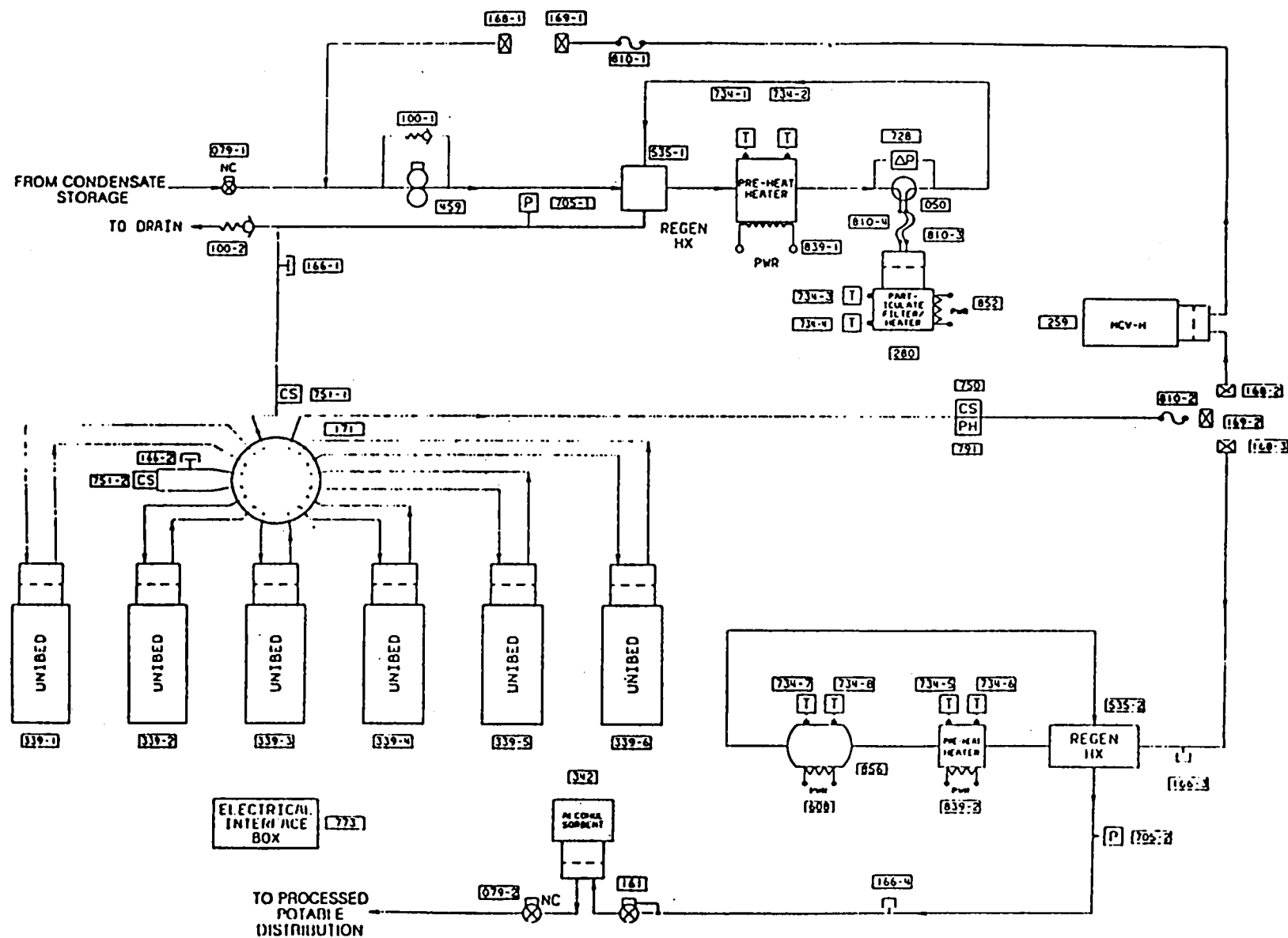
Reverse Osmosis System Schematic for Hygiene Water Recovery

HYGIENE WATER PROCESSING

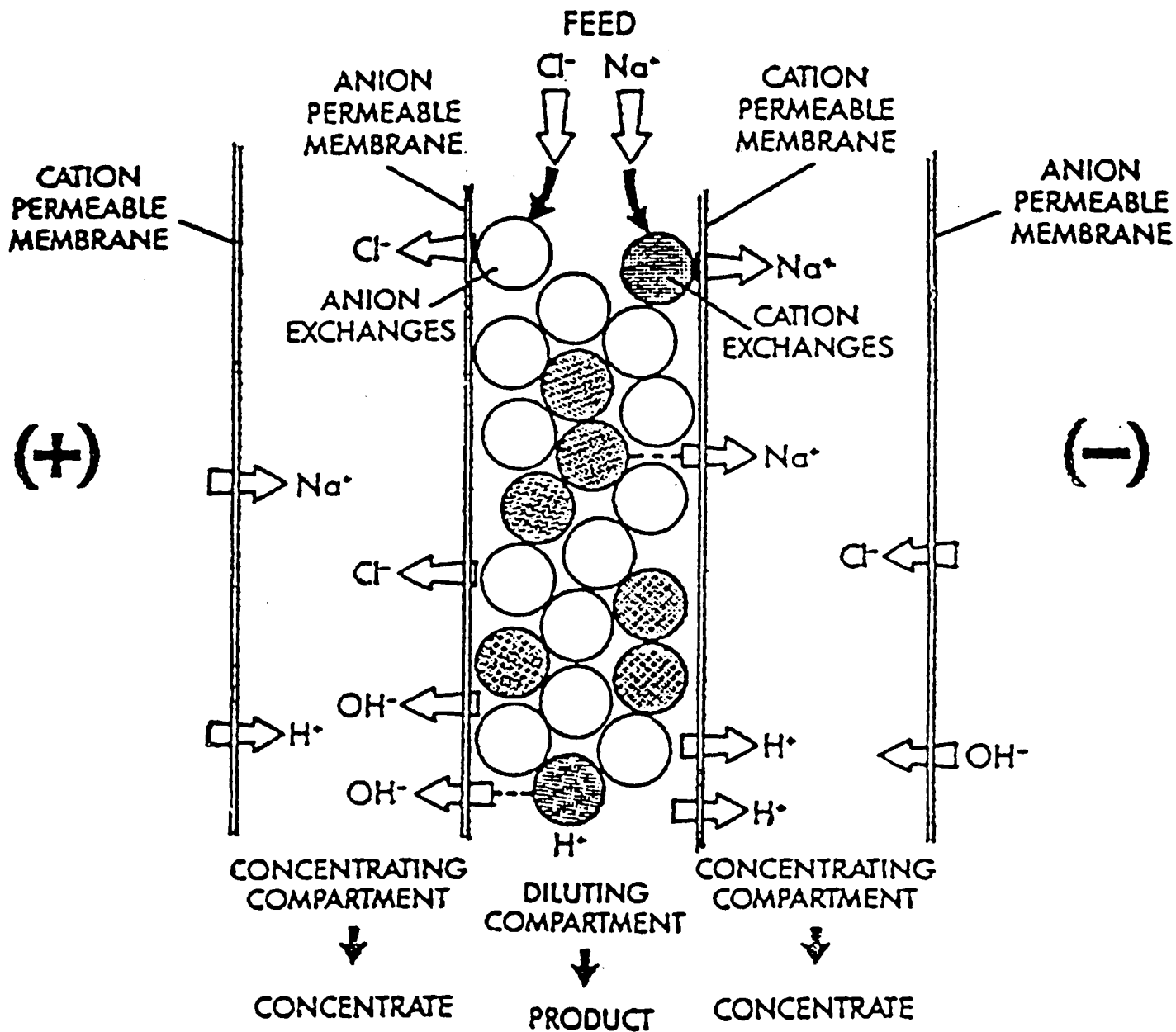
FLUID INTERFACES

TECHNOLOGY	FLUID INTERFACES	
	LINE IN	LINE OUT
Reverse Osmosis	Waste Wash Water/Urine Processor Product Water	Hygiene Water Brine
Multifiltration	See Potable Water Processing	

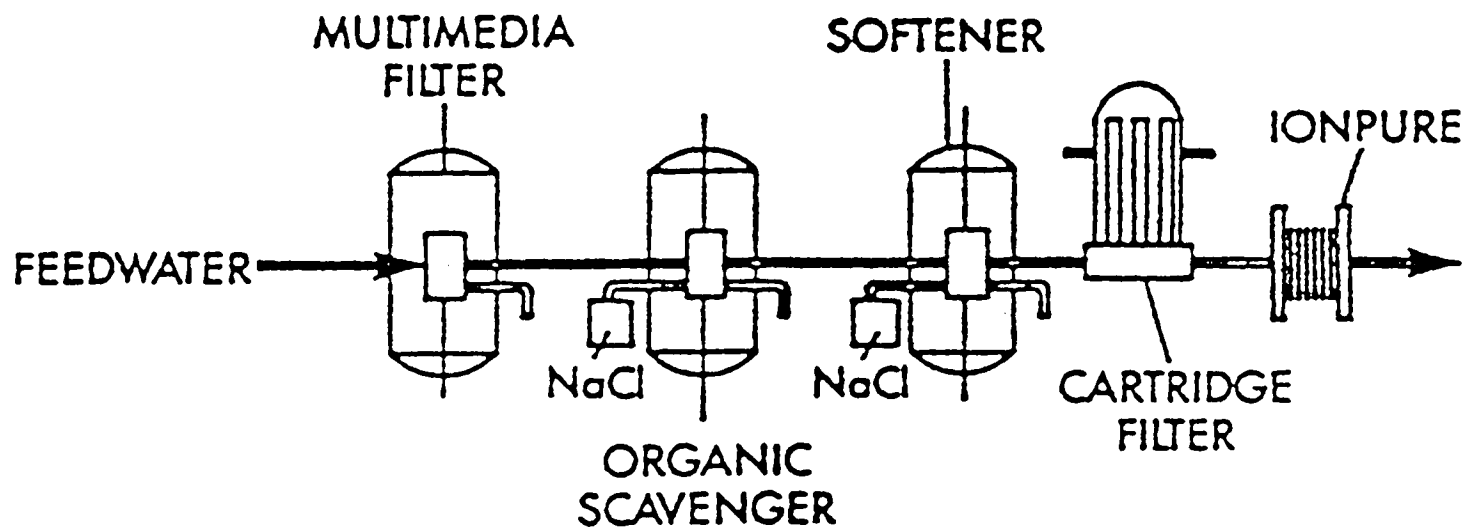
POTABLE WATER PROCESSING



Multifiltration System Schematic for Potable Water Recovery



The Electrodeionization Process



• ASSUMES FEEDWATER $SDI_{15} < 4.0$ AND FREE $Cl_2 < 0.2$ ppm

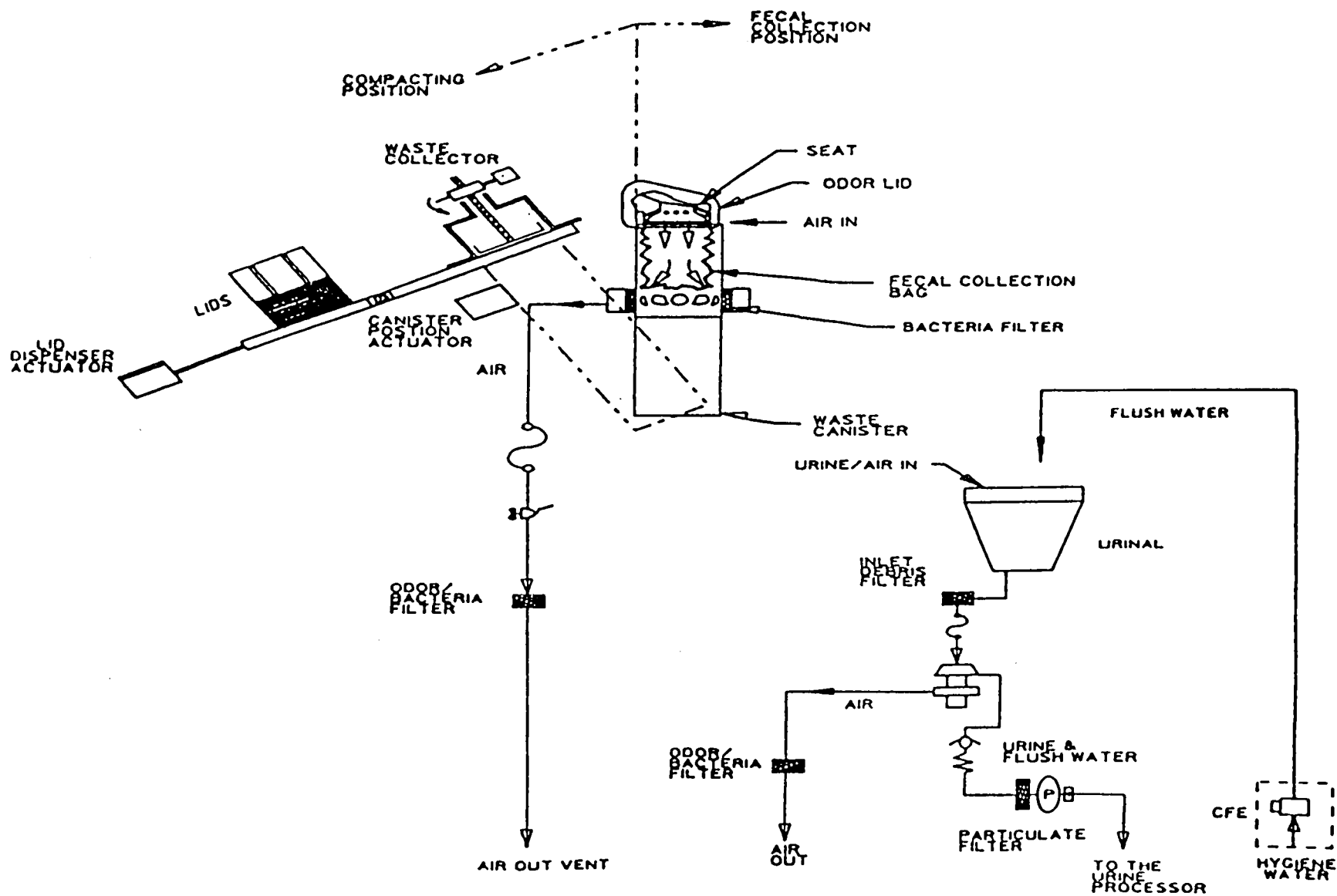
Electrodionization System ("Ionpure") with Pretreatment

POTABLE WATER PROCESSING

FLUID INTERFACES

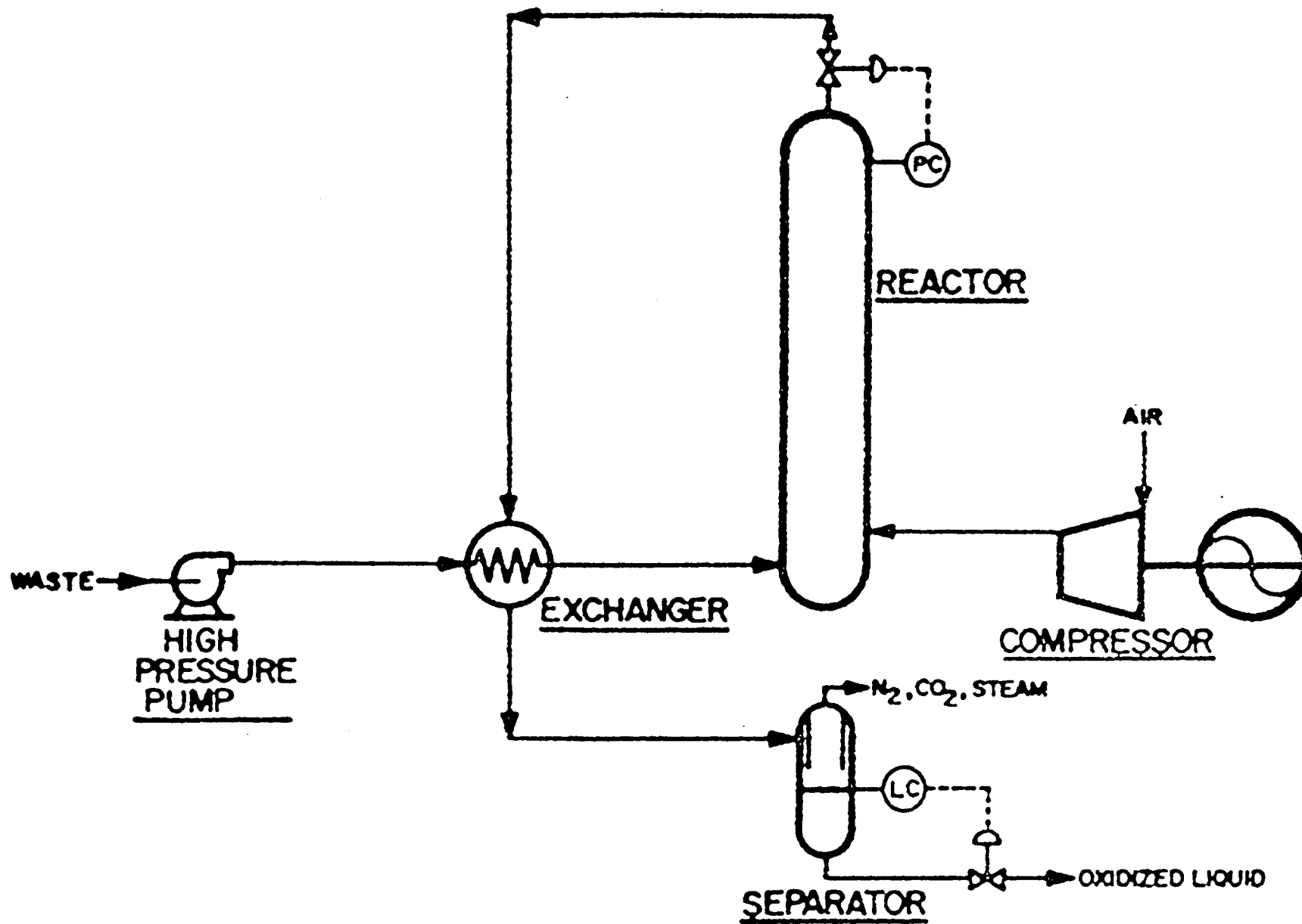
TECHNOLOGY	FLUID INTERFACES	
	LINE IN	LINE OUT
Multifiltration	Condensate from THC/CO ₂ Reduction	Potable Water
Reverse Osmosis	See Hygiene Water Processing	
Electrodeionization	Condensate Water from THC/CO ₂ Reduction	Potable Water Brine

WASTE MANAGEMENT

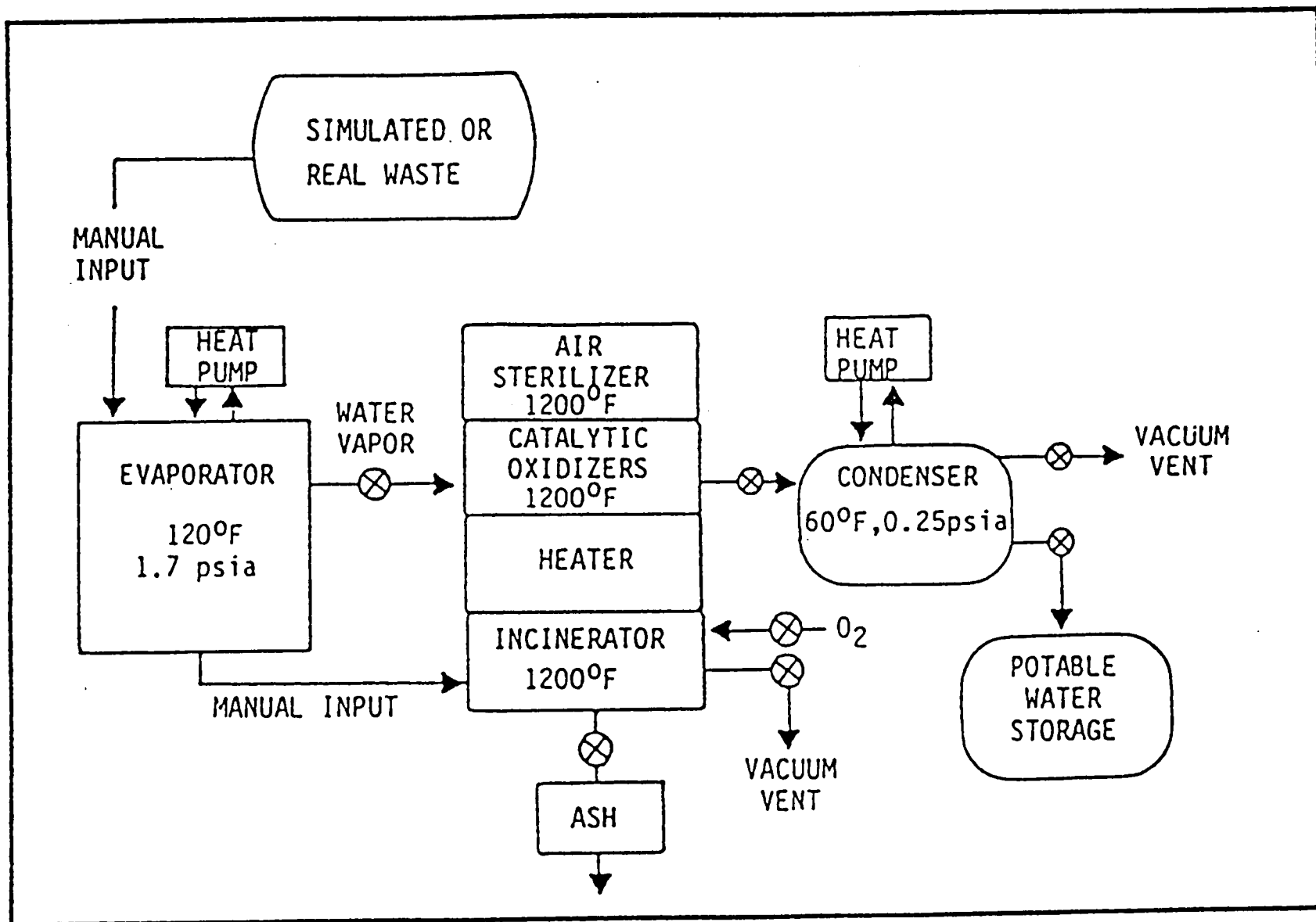


Schematic of the Baseline Urinal/Commode

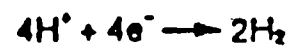
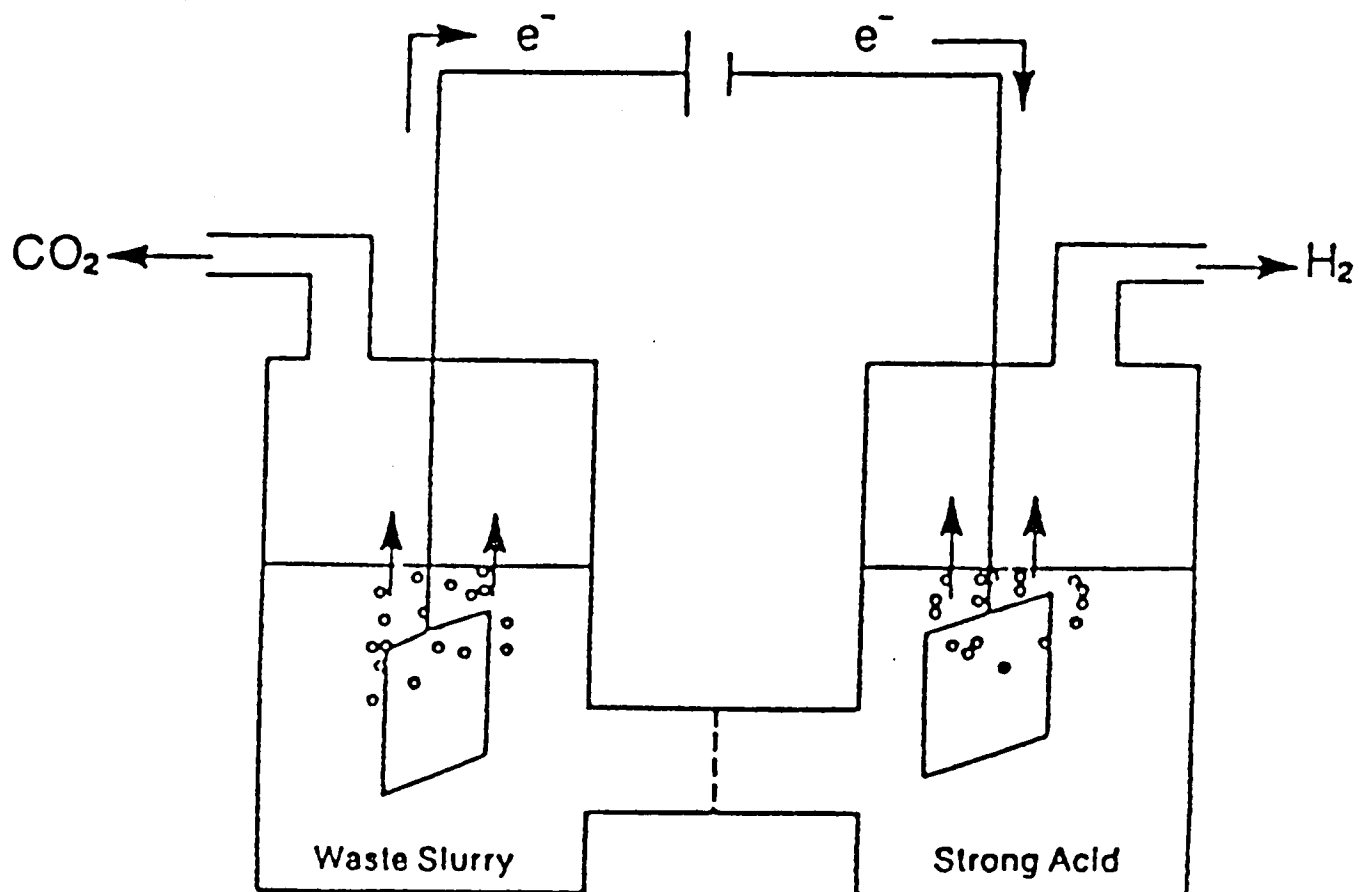




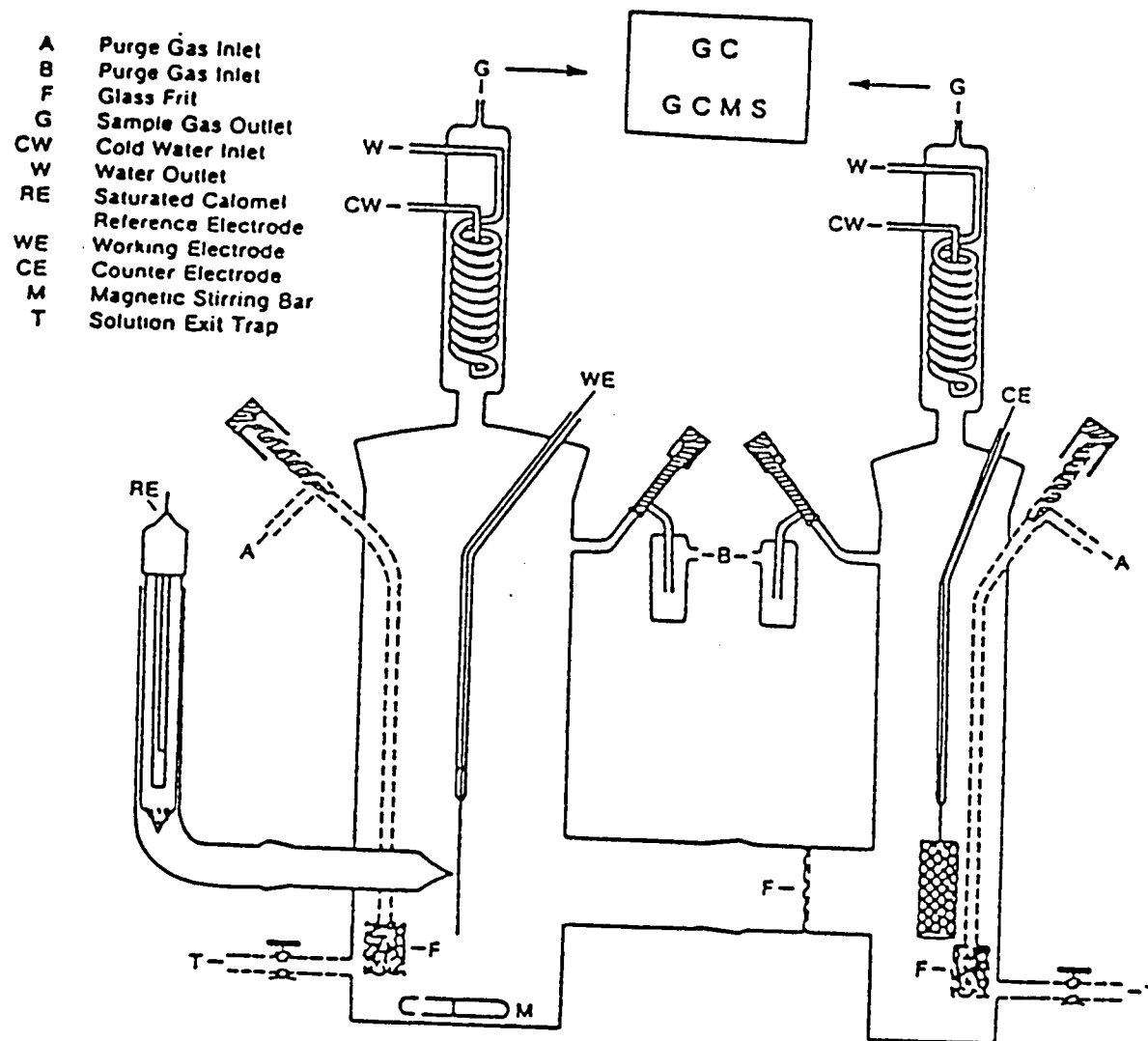
General Wet Oxidation Schematic



Block Diagram of Waste Managment - Water System



Electrochemical Decomposition Process Schematic



A Diagram of the Electrochemical Decomposition Electrolysis Cell

WASTE MANAGEMENT

FLUID INTERFACES

TECHNOLOGY	FLUID INTERFACES	
	LINE IN	LINE OUT
Storage and Biodegradation	Solid Trash/Human Feces	Return to Earth
Wet Oxidation	Waste Water Solid Waste, O ₂	Water and Gases to Posttreatment Solid Waste
Waste Management - Water System	Brine/Rejection Concentrates Air (from urinal)	Return Air Potable Water
Supercritical Water Oxidation	Cabin Air, O ₂ , Condensate, Wash Water, Urine/Flush Water, Solid Waste, Liquid Coolant	Return Air, Solid Waste H ₂ , N ₂ , CO ₂ to Storage Potable Water Liquid Coolant Vacuum Vent
Electrochemical Decomposition	New Concept - Interfaces undetermined	